SID 66-10

A Proposal For
AVAILABILITY EXTENSION STUDIES AS A MEANS OF EXTENDING THE USEFUL LIFE OF THE APOLLO SPACECRAFT

17 January 1966

Approved by

L. L. Kavanau
Executive Vice President - Technical

NORTH AMERICAN AVIATION, INC.
SPACE and INFORMATION SYSTEMS DIVISION

Reference File
DNO 65-853

FOREWORD

This document is the North American Aviation (NAA) Inc., Technical Proposal for Availability Extension Studies as a Means of Extending the Useful Life of the Apollo Spacecraft. It is presented by NAA's Space and Information Systems Division (S&ID) to the National Aeronautics and Space Administration (NASA) Manned Spacecraft Center, Advanced Spacecraft Technology Division. It is an unsolicited response to a recognized need for an immediate study of the Apollo extended mission reliability/ maintainability question.

The Cost and Contractual Proposal is submitted under separate cover.

CONTENTS

ILLUSTRATIONS

1.0 INTRODUCTION

The requirement for reasonable assurance in the nation's technological capability to successfully meet the extended missions reliability problem, presented by future AES and planetary exploration, has created a need for a design/operational concept which will produce the required assurance yet will be realistic and acceptable to all phases of engineering and management. The "no-failure-allowed" approach toward mission assurance is simply unrealistic for very long missions, at least within reasonable funding restraints and anticipated development cycles. The demand for a practical, workable, long-mission-duration manned space system has resulted in the need for concepts of design which lean heavily on optimal use of both man and machine in all facets of their joint capabilities. This, of necessity, includes man in the role of a maintenance expert, and as a trouble anticipating sensor, a backup operation, a backup computer, and perhaps many other functions as yet undefined. A design concept which tends to maximize the capabilities of the man-machine combination and provides the necessary assurance in mission performance is clearly required before a mission of more than three-month duration can be safely undertaken. Such an approach is embodied in the Availability Concept.

The Availability Concept, developed by NAA's Space and Information Systems Division (S&ID) for application to space missions, is a design/analytical technique which tends toward an optimum man-machine-mission relationship, assuring at least the required operational availability of the critical functions within the constraints imposed by the crew and mission commitments.

In regard to the maintenance aspect of the problem, studies conducted at S&ID have indicated that man probably can perform the majority of the required activities in the space environment given modest but adequate preparation. Indications are that the work load probably will not exceed one unscheduled maintenance action in a one-week period, and further, these requirements can be identified with a reasonable degree of accuracy. The uncertainty factor imposes a small weight penalty on the spares load.

Although the Apollo spacecraft was not specifically designed to facilitate maintenance, it does permit a certain amount and that which it permits can safely provide an increase in the mission duration by factors of 2 to 10 with little change in the basic design. The exact capabilities are unknown and this document proposes to explore the possibility.

S&ID herein proposes a three-phase study which eventually will lead to an optimized design for the Apollo Extended Mission requirement. The three phases are:

- Phase I - Determine what can be done to extend the Apollo Block II safe mission life without imposing any system design changes. The results are to be expressed in terms of safe life, spares, and operating procedures, for missions of up to three-months' duration.

- Phase II - Extend the Phase I studies to include mission durations of six months, but consider the inclusion of minor design changes such as improvements to and additions of access panels, fasteners, and plumbing and connectors (perhaps minor relocation of critical assemblies).

- Phase III - Extend the Phase I/Phase II studies to include missions of up to one-year duration, considering more extensive redesign of systems layout or packaging to provide for maintenance. The accent will be on optimal use of maintenance without redesign of components, that is, by improving the packing concept.

For the first phase, S&ID is proposing to use a team of five experts in the fields of reliability, maintainability, systems engineering, operations analysis, and ergonomics. In addition, these engineers will be assisted by consultants from the Apollo project, the AES team, and other areas of NAA. North American Aviation considers the subject effort fundamental to the advancement of the overall U.S. space program, and as such will take all steps necessary to provide the management and technical resources necessary to assure meaningful study results.

This proposal is presented in two parts: this document, the technical proposal; and, under separate cover, the cost and contractual proposal. The detailed task descriptions presented cover the Phase I effort. The remaining two phases will be planned in more detail during the latter tasks of the Phase I effort. It is expected that the first phase, as proposed herein, and the second phase will require a very modest effort. The final phase as recommended herein could be accomplished in conjunction with a future Apollo Applications Study and not add appreciably to the cost.

2.0 BACKGROUND

2.1 THE GENERAL PROBLEM

During the past two years, S&ID has been engaged in the study of the reliability problems associated with extended manned space travel. Much of the work has been accomplished under the sponsorship of the NASA contracts, The Manned Mars Landing and Return Study, NAS2-1408; and the Manned Mars and/or Venus Flyby Study, NAS9-3499. In addition, S&ID has continued these efforts through company-sponsored studies. These, in conjunction with the Apollo program and AES studies, have provided a wealth of data on the reliability/crew safety aspects of manned spaceflight problems.

Study results indicate that for missions in excess of about 45 days, it becomes increasingly impractical to attempt design of a spacecraft for maintenance-free operations. This situation probably will prevail for at least a decade. The practical mission limits for a pure reliability or nonmaintainable design for a manned spacecraft have not yet been determined. It is certain that the useful life would vary with the mission profile and objectives; much can be gained from proper control of these factors. It is obvious, however, that as missions are extended in duration and the abort profile becomes more complex and time consuming, a point will be reached where adding redundancy no longer will compensate for potential failures but rather add to the overall failure hazard. It is then that maintenance must be considered as a more reasonable alternative. This can be demonstrated theoretically by the use of the estimator for mission reliability (R) or the probability of no failure in a typical state-of-the-art spacecraft.

$$R = e^{-t/M}$$

where:

t = mission duration or duty cycle

M = Mean Time Before Failure or MTBF

The typical state of the art spacecraft MTBF is estimated to be about 2800 hours. Now, assume that the mission duration is about 400 hours. Without any repair the probability of mission success (no failure) is only:

$$R = e^{-\frac{400}{2800}}$$

$$= 0.870$$

By making just one repair it is increased to at least

R = 0.933 at the lower bound

and could be as high as 0.99 depending on the assumed distribution and/or how the provision for the repair was implemented. Adding provisions for one more repair (in the critical system), or a total of two, raises the lower bound estimate for mission reliability (R) to more than 0.99. These data indicate that providing for maintenance for the longer missions possesses a very attractive potential for increasing probability of mission success. Further, this is one case where the mathematics present a very conservative picture of the actual gains derived. This effect is dramatically shown in Figure 1 which presents an estimate of mission reliability as a function of mission duration and spares application. The lower curve, the baseline spacecraft, is representative of the latest AES reliability estimates derived from Apollo data. The curves above the base spacecraft represent the effects of adding one spare to the previous state for replacement of a critical component in the listed system. Note that only three spares have produced a marked effect on mission reliability.

The effects of sparing on crew survival probability are not as dramatic for the earth orbital missions; however, for the extended lunar and planetary missions, the results of sparing are essentially the same as shown for mission success. This condition prevails because of the abort criteria applied to the Apollo missions and the very high initial probability of crew survival. But, as the missions are extended in distance away from the earth, the abort time delay exercises an increasingly more significant influence on the survival characteristics of a nonmaintainable design.

There is, of course, nothing new about maintenance. It has been done for years, although usually in spite of the design, rather than as a result of designing for maintenance. Figure 2 presents an assessment of the contrast in maintenance time required on a typical communication system before and after it was packaged for maintainability; note that the "after" mean time to repair (MTTR) was reduced to less than half the original time.

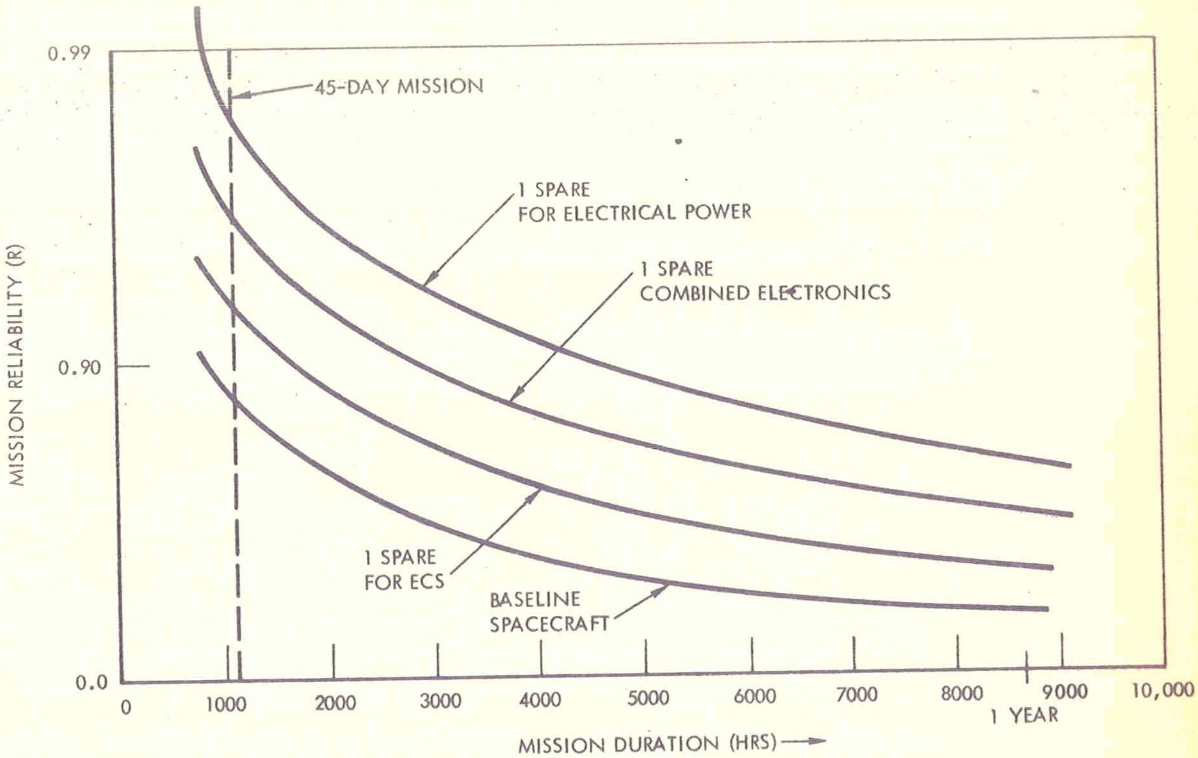


Figure 1. Spacecraft Probability of Mission Success as a Function of Mission Duration and Simple Sparing

On the other hand, space working conditions do impose restrictions on maintainability, predominantly in the form of an increase in repair time. Some of these effects may be seen from Figure 3 which presents the results of a cursory analysis which has been verified to some extent by recent ergonomics studies conducted by Dr. Streimer of S&ID. These data were collected on the six-degree-of-freedom simulator at the S&ID Ergometrics Lab. The data collected to date indicate that after about 20 attempts at a particular task, the accomplishment time levels out. Zero g seems to have little effect on the time to repair if the proper restraints are provided; however, the energy requirement about doubles.

The space suit seems to exert the most pronounced influence on task time. A partial suit will increase the time to repair by a factor of two and the complete suit by a factor of four with the energy requirements increasing proportionally. Preliminary data indicate that most maintenance activities can be accomplished without the encumberance of the space suit, with a ratio of more than 20 to 1. Clearly, maintenance can be accomplished but the problems must be bounded and the design thereby constrained.

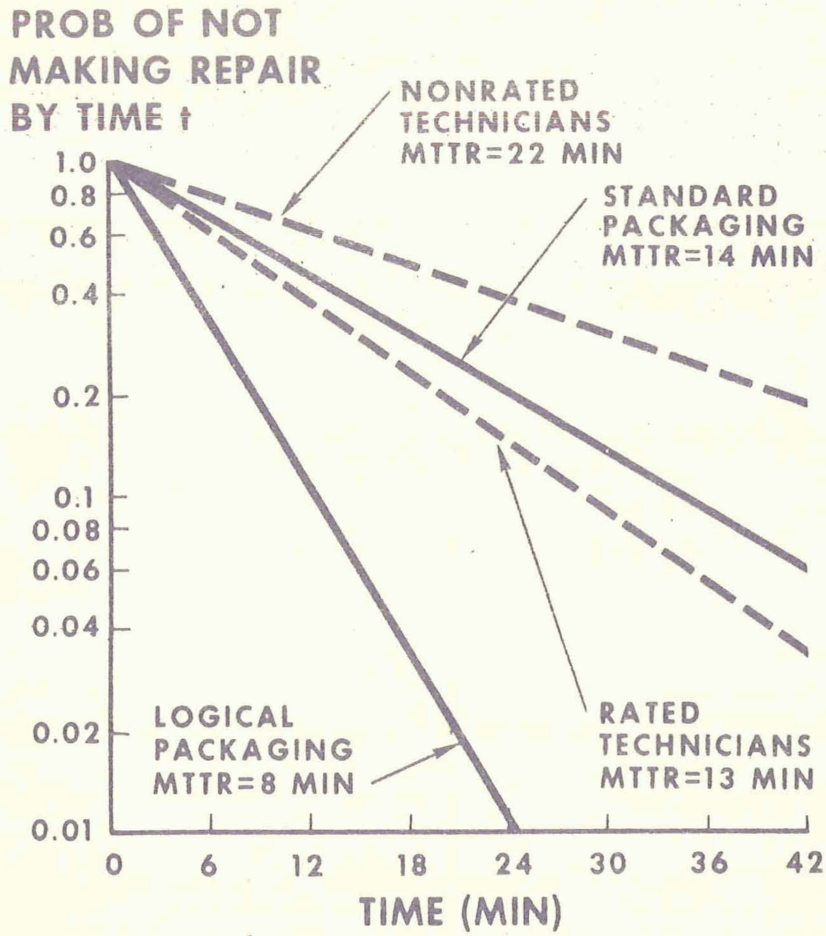


Figure 2. Effect of Design and Training on Maintainability

The problem that confronts the spacecraft designer is twofold: (1) determining how to deal with the problems of maintainability in the space environment without adversely affecting the crew; and (2) establishing, with reasonable assurance, what will fail and when.

As a result of analysis conducted by S&ID during the referenced planetary studies, a mission and systems requirements analysis technique, the Availability Concept, has been developed and successfully applied to these problems. An extension of these efforts is proposed herein.

2.2 THE APOLLO EXTENSIONS PROBLEM

With the advent of the extended mission (more than 45 days) programs, the questions of reliability, mission success, and crew survival are brought to the fore. Since reliability is recognized as an inverse time-dependent

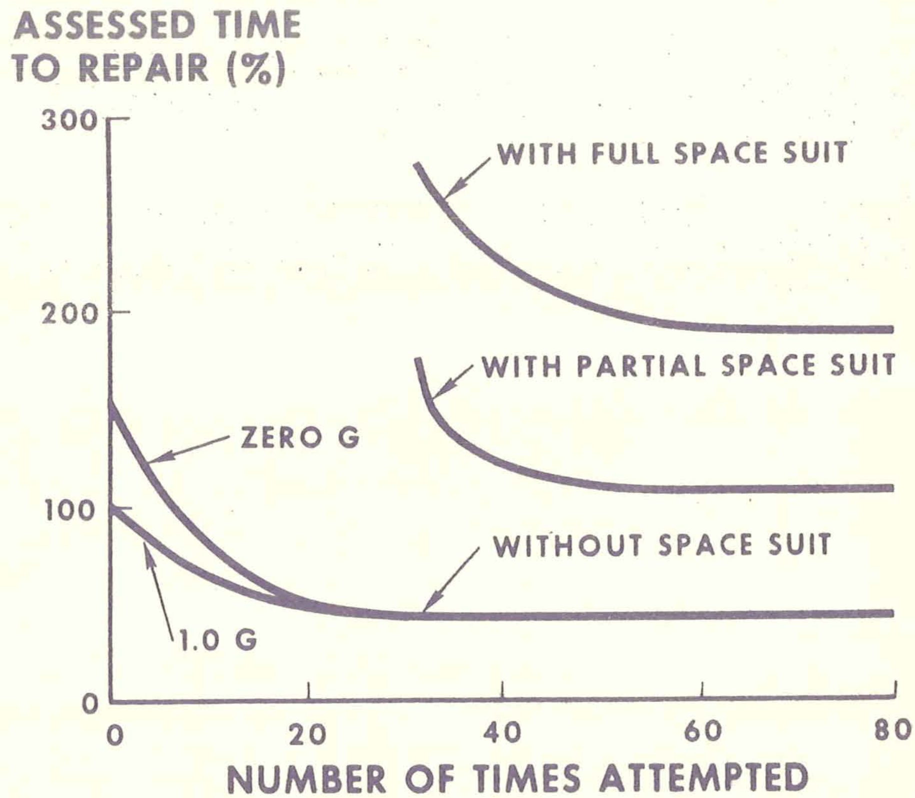


Figure 3. The Effects of Space-Imposed Working Conditions on Task Time

function, it follows that there is a point in the spectrum of mission duration beyond which it is not technically and/or economically feasible to provide the desired assurance in safety and/or success without resort to maintenance. The first problem associated with the extended mission programs is that of identifying just where it is either necessary or desirable to revert to a planned maintenance program. The answer must be in terms of a probability function. Figure 4 presents some "ball park" probabilities associated with the major spacecraft functions as well as the total vehicle systems. The scientific and other non-crew-critical functions are not included. A detailed study is required to determine the exact relationships among the various categories of specific mission objectives.

The advantages of redundant design have been explored by the present S&ID AES effort and maximum use of this technique plus duty cycle control has been used almost to the limit of contemporary technology. Probably little if any more can be gained from this approach for the next decade. The limits of this concept may be seen from Figure 5 which relates

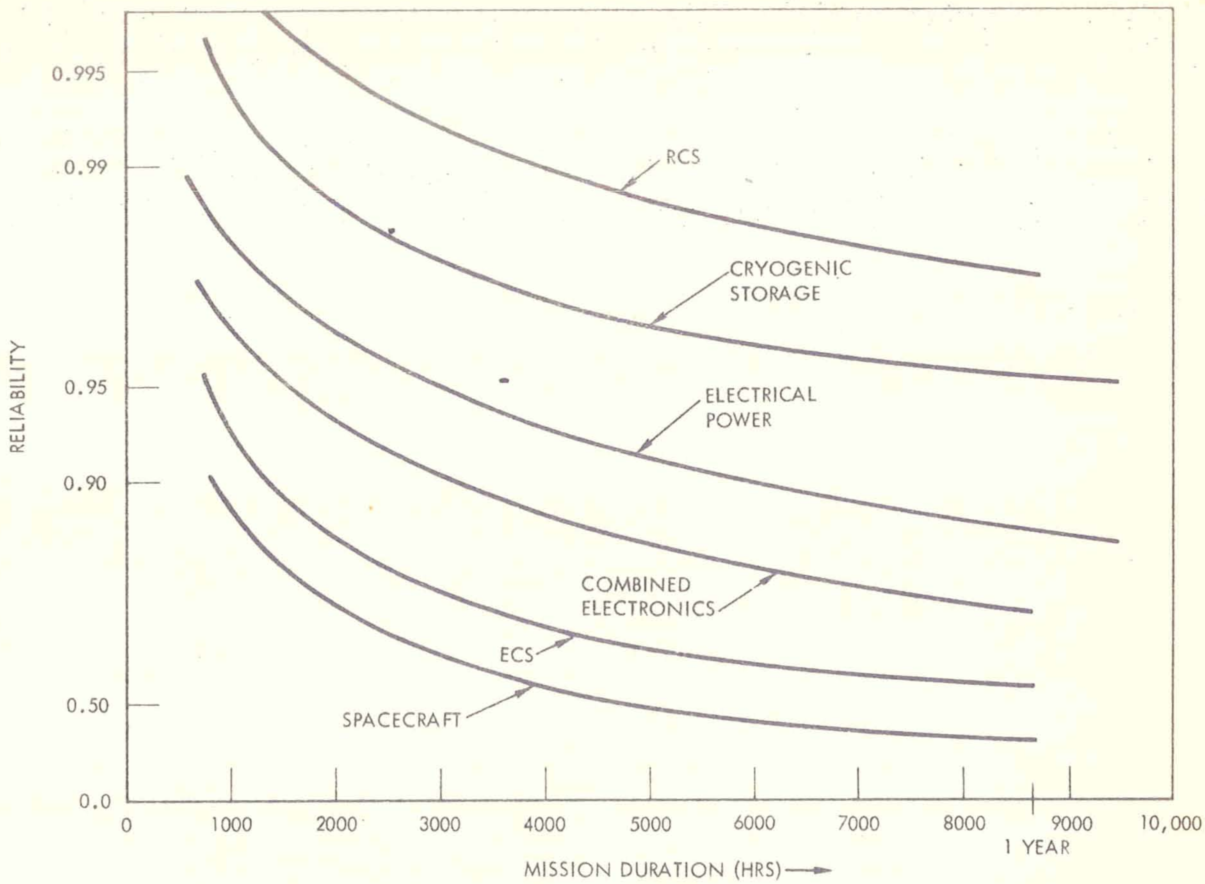


Figure 4. Projected Spacecraft and System Reliability as a Function of Mission Duration

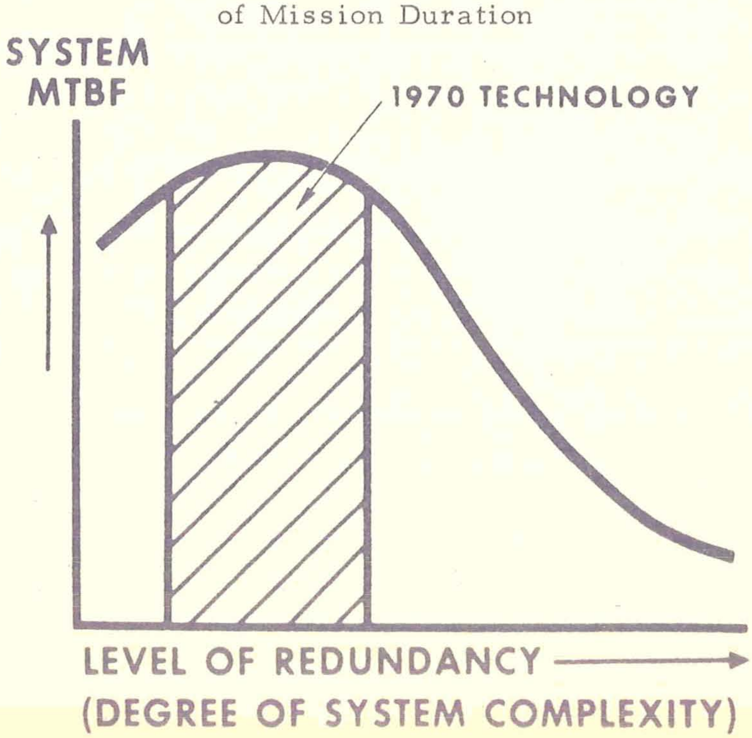
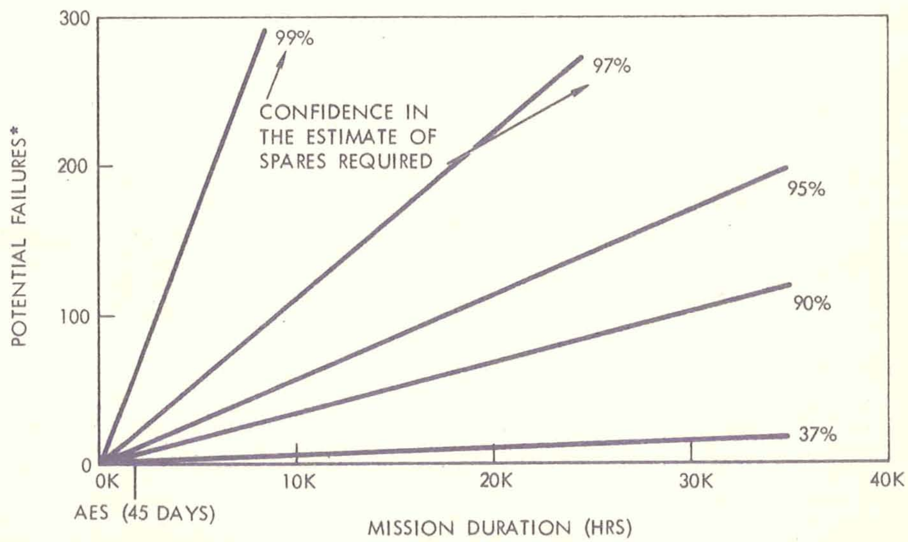


Figure 5. Equivalent System Mean Time Before Failure as a Function of Redundancy and State of Art Limits

the problem in qualitative form; adding redundancy, active or passive, beyond the optimum reduces the ultimate overall mission reliability because of the associated increase in power requirements, complexity, monitoring, wire in, switching, and control requirements.

As indicated previously, the number of maintenance actions expected are not excessive and the time constraints are within the astronauts' capabilities. Figure 6 presents a gross estimate of the number of unscheduled vehicle systems maintenance actions expected as a function of mission duration. During the proposed study this will be refined and will encompass various classes of missions. The estimate indicates that for more than 95 percent of the missions, there will be less than one unscheduled repair action required in any seven-day period after the initial phases of the mission.



*AT THE INDICATED PERCENTILE, USING STATE OF ART ESTIMATES AND ASSUMING AN EXPONENTIALLY DISTRIBUTED FAILURE HAZARD.

Figure 6. Expected Number of Failures for the Vehicle System of a Contemporary Spacecraft as a Function of Mission Duration

3.0 MAINTENANCE CONCEPT FOR APOLLO - BY THE AVAILABILITY CONCEPT

3.1 THE CONCEPT

Recognition of the high probability of failures on the long space missions and the understanding of the need to learn to live with them seem essential to a successful exploration program. But this does not constitute a reason to postpone the extended missions. The possibility of failure does not mean, ipso facto, mission catastrophe. Consider the results of our space programs to date—the many failures with no crew loss. Realization of this important fact led S&ID to the development and application of the Availability Concept.

By definition, the Availability Concept is a design/mission analysis technique that facilitates the determination of an optimum man-machine relationship. With this technique, mission effectiveness is maximized through establishment of a safe and reasonable balance between system and mission performance, reliability, and maintainability. Application of this concept can result in a design which provides maximum operational availability of the system functions within the constraints imposed by crew capabilities, mission requirements, and the existing state of the art.

The difference between the availability concept, when applied to a system/mission design, and the "reliability-by-redundancy" approach is demonstrated by the two curves contrasted in Figure 7. The ordinates R and A both express the probability of mission success. However, the ordinate A is independent of time but dependent on maintenance and meeting the downtime constraints. In the situations portrayed, the mission time approaches, or is in excess of, the system MTBF. Note that with the pure reliability approach, the longer the mission duration, the more probable failure becomes with the result that the longer missions are doomed to almost certain failure. With the availability design, there is no appreciable change found in the probability of mission success within the mission duration indicated. This remains true as long as the spares level is adequate and the imposed time constraints can be accepted.

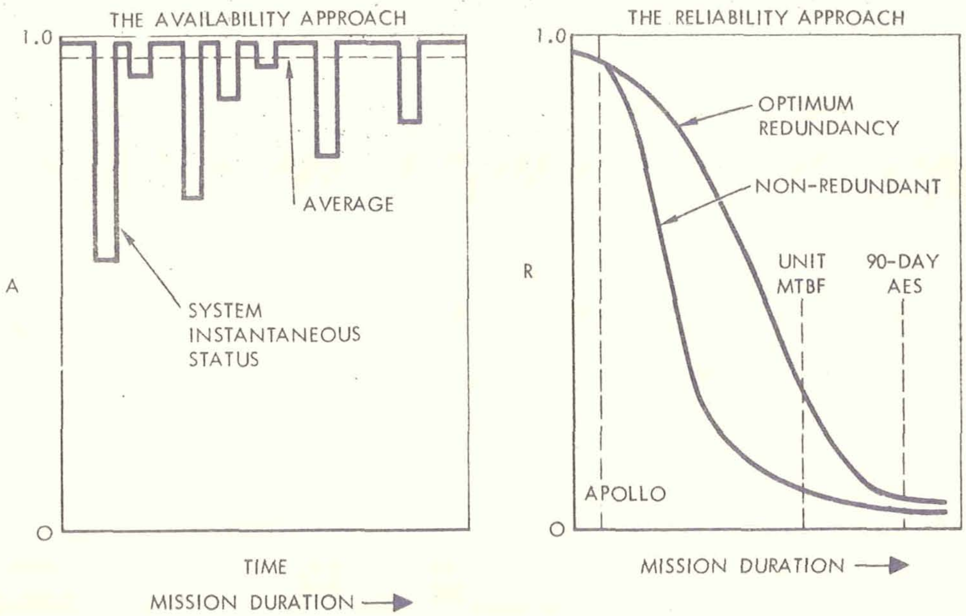


Figure 7. Reliability Concept vs. Availability Concept for Long Missions

3.2 APPLICATION CONSTRAINTS

3.2.1 Systems Downtime Constraints

One of the most critical problems to be solved, or bounded, is the tolerability of a mission system to failure. First, it must be shown that any probable failure in the system will not result in immediate loss of crew or mission and, second, that there is sufficient time to make a repair before the failure does result in loss of crew or mission.

There are two critical categories of constraints imposed on the spacecraft systems. Each of these systems must be evaluated under these constraints and in terms of the functions provided. The critical constraints will be imposed either by crew physical requirements or by spacecraft profile/attitude requirements. Noncritical classes are imposed by crew psychological requirements or scientific support systems.

The analysis of mission constraints on failure duration, as imposed by any specific system function, usually reveals a very noncritical situation because of the multiple redundancy within, as well as between, systems. This is particularly true when man is treated as a system. For example, if all the power were out, he could manually feed O_2 into the cabin or his suit and purge it periodically for quite some time, or he could use his back pack. Functional backup, external to a given system, is sometimes available, but should not be considered under the downtime constraint analysis, since a design action may later eliminate the advantage.

This leads to the definition: A downtime constraint or maintenance time constraint (MTC) is a restriction imposed on the total allowable elapsed time that a system function can be out of service before a situation is created that would be deleterious to either crew performance or the mission.

Figure 8 presents a sample functional diagram of a typical environmental and life support system to demonstrate the origin of some of the crew-induced constraints. Crew requirements are divided into inputs and outputs which may be regarded apart from the mission, but must be considered in conjunction with a spacecraft design, or at least a specified cabin size, since some of these are a function of the ratio of volume to number of men.

The determination of crew-induced constraints may proceed as follows:

1. List all of the isolatable functions provided by the system. The further along a system is in the development cycle, the more detail the analysis should reflect.

2. For each function, determine the MTC using the definition previously given. Usually it will be found that there is no sharp line of demarcation, but rather a gradual degradation in some performance parameters. For example, the CO_2 removal function may be "down" (inoperative) until the concentration reaches a partial pressure of about 8 mm of H_g, where the concentration may cause headaches, but even after that the crew will continue to function for many hours at reduced performance. World War II submarine data support this observation.

   As another example, consider the spacecraft stability-control system. If it were completely inoperative, it is estimated that

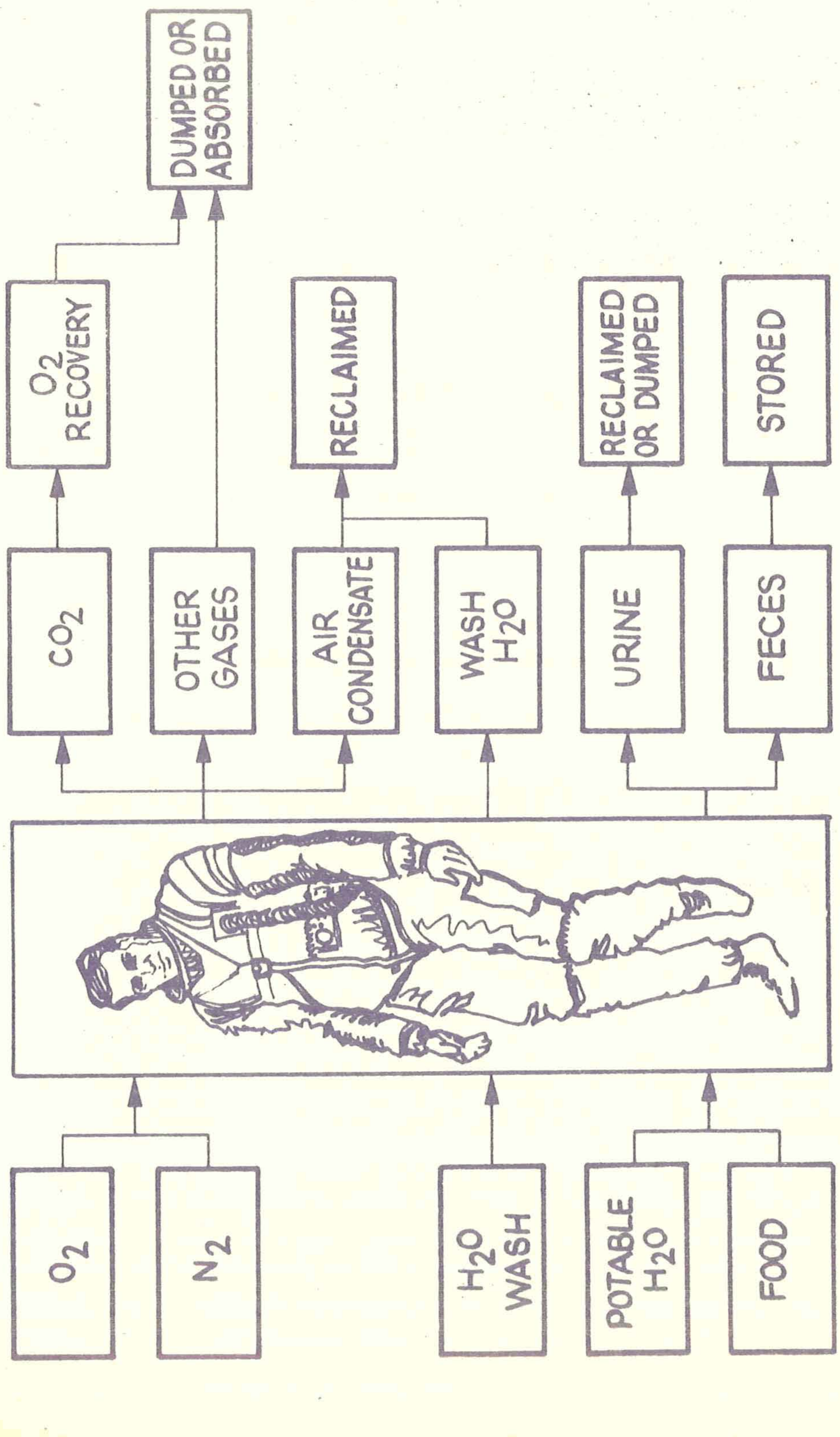


Figure 8. ECLSS Function

it could take up to eight hours before spacecraft tumbling would become objectionable. Even after that, maintenance could probably be performed in spite of the adverse circumstances.

3. Where possible and applicable, it is desirable to set two constraints - one for degraded performance and one for catastrophe.

Table 1 presents some sample constraints resulting from the analysis of a typical ECLSS at the level shown in Figure 8.

3.2.2 Profile-Induced Constraints

MTC's also are influenced by the selected mission profile. They result from the need to perform some action at a specific point in time, i.e., they are non-deferrable. MTC's will vary considerably with the specific mission profile, and therefore they present some useful arguments for selecting the least complex mission profile. It is evident that the less a spacecraft is expected to do during a mission, the more reliable (numerically speaking) the mission will be. It follows that the lower the number and the shorter the duration of programmed operations or maneuvers, the less restrictive the induced downtime constraints will be.

Figure 9 contrasts a simplified, typical planetary or lunar-landing mission profile with the flyby profile. It is estimated that a typical flyby profile requires no more than 16 discrete major spacecraft operations, whereas the landing missions, using rendezvous techniques, require at least 38 operations of a similar magnitude. Since this analysis is specifically concerned with downtime restrictions, these operational restrictions can be determined as follows:

1. List each operation required in chronological order (time line profile).

2. Determine the spacecraft subsystem/functions required for each operation listed.

3. Determine if the total operation is deferrable and establish the time boundary - in parametric form where required (i.e., for ΔV, time vs. fuel).

4. Determine the resulting downtime constraints as imposed on the constituent subsystem functions.

Table 1. Sample Downtime Constraint Analysis, Environmental Control System

Assembly Function	Maximum Allowable Downtime (hour)	Maximum Anticipated Downtime at 99 Percent (hour)	Downtime Constraining Factor
Space radiator valves	8	1.5	Depends on power source cooling load and minimum electronic equipment requirements
Water-glycol pump	6 to 8	Motor to 0.4 Pump 2	Depends on power source cooling load and minimum electronic equipment requirements
Cabin temperature control	8 minimum 24 maximum	1	Temperature rise in cabin due to all equipment operating
Check valve and glycol shut-off assembly	6 to 8	2	Depends on power source cooling load and minimum electronic equipment requirements
Pressure suit heat exchanger	Normally unlimited 2 to 4 hours in use	2	Temperature rise in suit
Suit hose connection	Normally none, 0.5 in emergency	0.5	Depends on use requirements, back pack provides a backup mode
Water-glycol loop	6 to 8	2 maximum	Limited by emergency cooling load such as electronic power
Suit circuit	Normally none, 0.5 in emergency	2 maximum	Depends on use requirement, back pack can provide backup
Cabin flow valving	24 with backup system	1	Backup system
Water check valve assembly	24	2	Backup system
Water tank pressure relief	Normally none, manual control possible	None due to redundant valve	Tank overpressure
Water tank pressure control	Normally unlimited with manual control	1	Tank overpressure or underpressure
Cabin heat exchanger	8 minimum, 24 maximum	2	Temperature rise in cabin due to equipment operation
Cabin pressure negative relief	Normally none, manual backup	1	Cabin overpressure
System limits		Unknown	Electrical power system

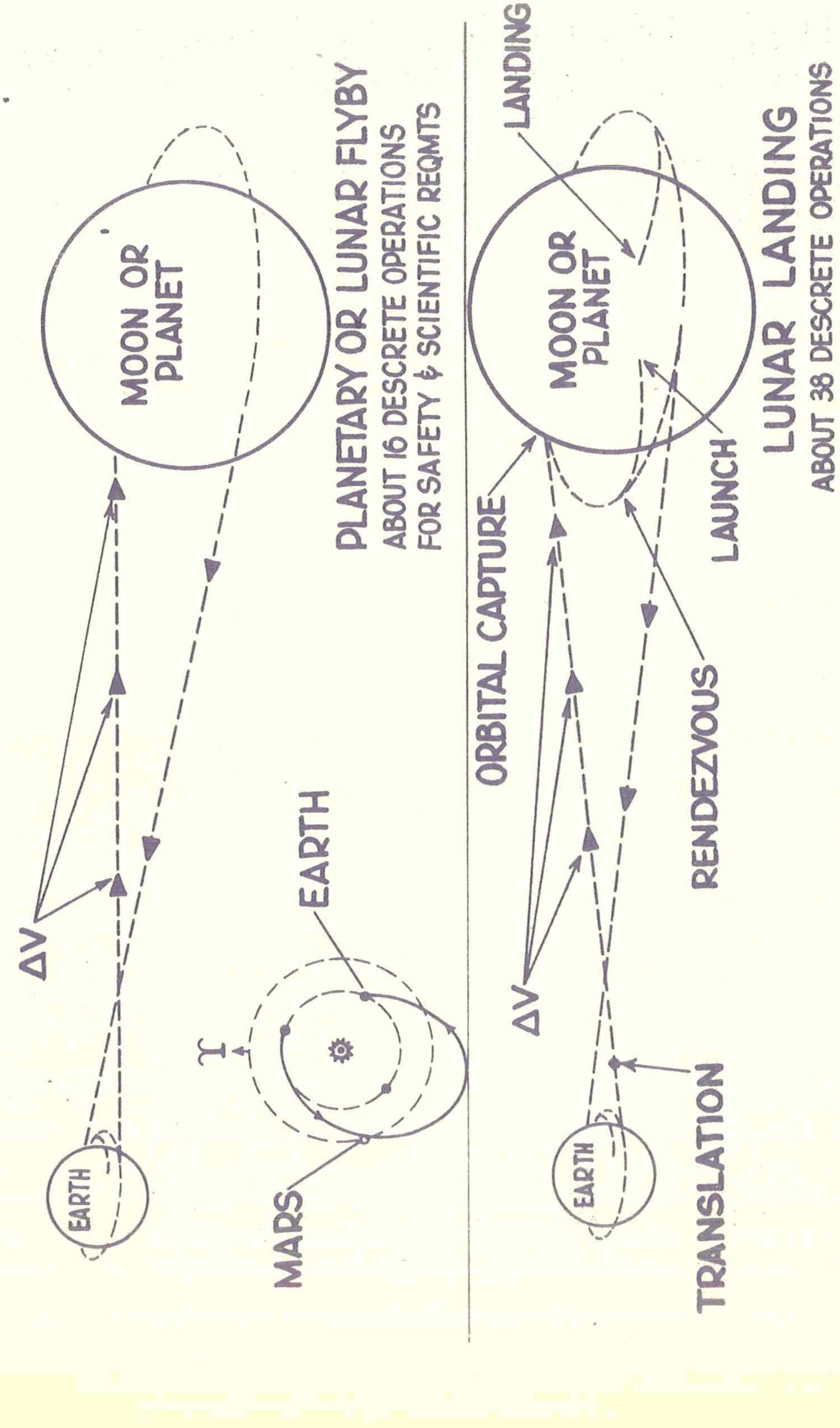


Figure 9. Profile Constraints Analysis

The analysis of the flyby profile data demonstrates that, for this profile, the only critical phase is earth approach and reentry which lasts for no more than about two hours. A simple reliability calculation, using the most pessimistic approach, would reveal a very high probability of no failure during this period, providing the systems are checked and operating prior to phase entry.

3.2.3 Spares Weight/Volume Limitations

Since it has been established that there is more than reasonable degree of probability that systems and the function they provide will fail during the longer missions, spares must be carried to facilitate repair. In opposition to this requirement is the ever-present objective of minimizing overall weight and/or volume. For long space missions, the number of spares carried directly affects the level of crew safety. Figure 10 presents a set of curves expressing the relationship of mission success and crew safety as a function of spares weight carried and risk for typical missions of one-year duration. Note that the differences between the mission success and crew safety curves are due to the requirement to service such auxiliary equipment as the scientific instrumentation and TV system.

During the early days of the Apollo project and prior to the incorporation of redundancy, it was estimated that up to a hundred pounds of spares might be required to raise the reliability prediction to the objective for a 400-hour lunar flight. A later study showed that an additional 300 pounds were required to raise the same systems to a reasonable level for a 120-day earth orbit mission. The referenced planetary studies demonstrated that about 1000 pounds of spares might be required for mission assurance of a typical one-year mission using a maintainable version of the Apollo design.

3.2.4 Astronaut Maintenance Capability

Since repairs must be made, at least one astronaut must be capable of performing the repair. This implies a training program in anticipation of these specific events and an estimate of the kinds of repairs to be made. This may seem a most difficult problem, but a close examination of the Availability Concept reveals a possible approach. It is based on the premise that astronauts cannot repair or replace any equipment for which they do not have spares and they need be trained only to implement the chosen spares. This practical limit assures maximum possible contribution to the probability of survival without saturating the astronaut with useless data.

Backup to the training program and the resultant capability can be provided in the usual form of service manuals, system diagrams, but more

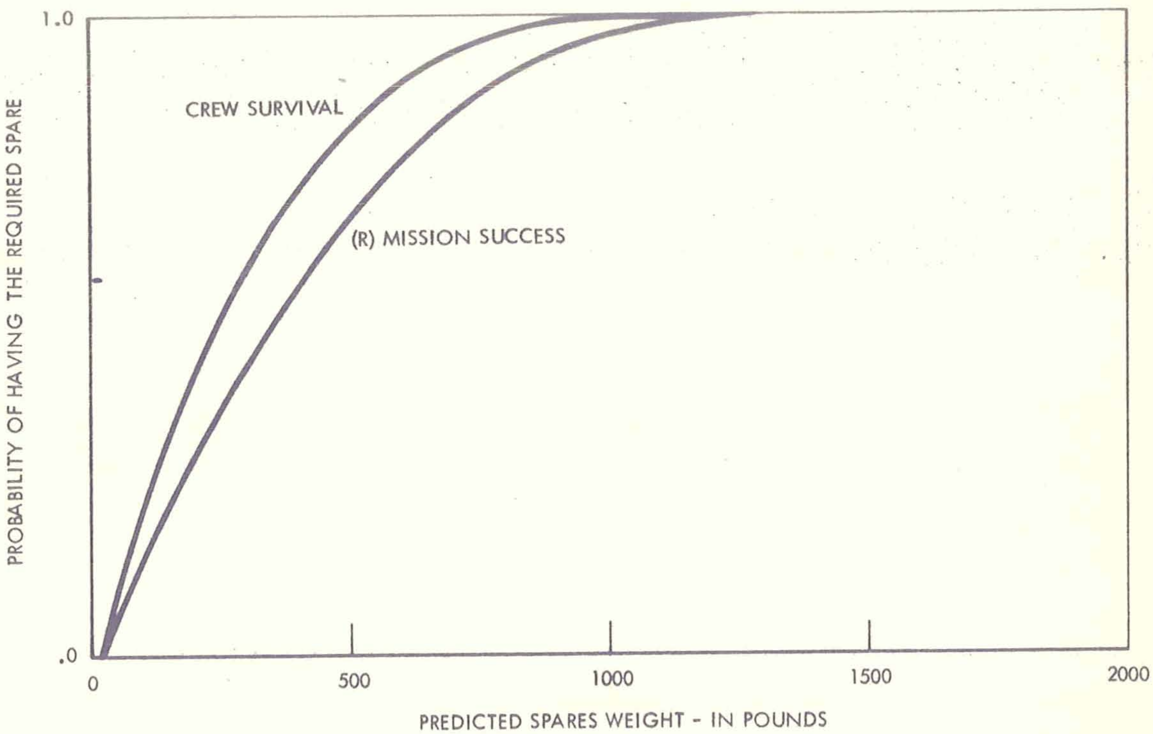


Figure 10. Estimated Spare Weight for a One-Year Mission

particularly through the radio or television links. In any event, the number and kinds of documentation required to implement the usual maintenance plan will not be required. In addition, the diagnostic routines will be far less complicated since the probable failures and associated modes will be known.

The problem of astronaut capability has been discussed to some extent in a prior section, but since the impediment imposed by zero g and the space suit must be considered in estimating requirements and sizing systems, a reiteration is in order. It is known that the human operator executing a self-paced task normally limits his energy expenditure rate to between 800 and 1300 Btu/hr thus preventing his going into a state of oxygen debt. Because, in some cases, he must offset the restraining effects of a pressurized space suit and/or provide bracing for work, a limited amount of energy may be available for conversion to useful work. Work schedules and downtimes must be analyzed in light of these constraints.

3.2.5 EVA Constraints

Man's capabilities unaided under EVA conditions are known to be extremely limited. In fact, without some external maneuvering control, he has very limited capability to perform useful work. The work he can perform is therefore directly proportional to the capabilities of his restraining or stabilization aids. If he must apply 10 pounds of force in translation to work a latch, his Astronaut Maneuvering Unit (AMU) must possess at least that capability or a restraining system must be supplied which is capable of equalizing the vector. If he is forced to brace himself, the energy requirement is doubled and his useful work output capability halved.

S&ID has been studying the EVA control/stability problem for the past two years. The maintenance requirements vs. capabilities of the astronaut in free space was found to leave much to be desired. It was found that the best approach to the stabilization problem is to use a momentum exchange type attitude control system in the Extravehicular Maneuvering Unit, thereby providing constant stability with the lowest possible fuel expenditure for stabilization. Such systems provide the stabilization torques by the momentum exchange principle rather than reaction control jets. These momentum exchange devices (reaction wheels, control moment gyros) have finite momentum capacity and therefore will provide the stabilization torque for a limited time only unless the disturbance torques are cyclic. S&ID has built and tested an astronaut maneuvering unit based on a unique version of momentum exchange type attitude control. The control system used in this unit uses the dual purpose gyro system which is based on an unusual combination of six control moment gyros. The approach offers a multitude of advantages over other more conventional control systems of this type and will be used as a reference during the study for determining man's EVA capabilities and working constraints.

3.2.6 Other Constraints

A few other constraints appear worth considering at this time, all of which are the result of having to perform maintenance. These include the need for accurate performance monitoring (PM) equipment which will provide timely warning of impending problems. The PM must be able to signal the astronaut of a failure and isolate it in time for him to meet the MTC. In addition, tools and accessibility must be considered to facilitate the planned repairs. Note that all these requirements can be geared to the established spares level and contribute to that level of crew safety.

4.0 MAINTAINABILITY VERIFICATION

4.1 THE APPROACH

Given that the inclusion of a maintenance concept is the most effective and safe approach for the longer AES and planetary missions, it then is desirable to verify that maintenance can actually be performed on the particular spacecraft (Apollo Block II). Two levels of investigation seem pertinent; first a determination of what can be accomplished without change and then what minimum changes are required to assure maintenance of critical functions within the given time constraint.

To establish the potential feasibility of in-flight maintenance of Block II Apollo and the subsequent ability to extend mission life by this means, several maintenance examples were selected on a random basis to be presented. The selection of examples was dependent on available photographs, data and/or mockups for maintenance task analysis. As a result, the selected examples represent a wide range of accessibility problems and associated task times. Therefore, the probability of performing maintenance within the stipulated downtime constraints is not necessarily representative of the true capability for the Block II design and certainly not representative of what could be accomplished by even minor repackaging for maintainability.

4.2 SAMPLE TASKS

The sample tasks selected represent a cross section of potential tasks, selected from both electronic and electromechanical systems. Table 2 presents the inflight maintenance analysis of four potential tasks. Figures 11 through 14 present photographic evidence of the first three components. No photos were available of the fourth component, which is expected to be a weak link. Table 3 presents the isolation and task time analysis of these examples. Note that in three of the four cases investigated the tasks could easily be performed within an hour, which is known to be less than the expected downtime constraint. Again, these require no change to the present Block II configuration. Further, Task 4 is expected to be one of the most necessary tasks.

In addition to these presented, there are many other functions estimated to be maintainable in their present state; for example, the G&N temperature control system or the portable life support system. These and other areas will be investigated in the order of their potential effect on the probability of mission success.

Table 2. Inflight Maintenance Analysis

Provided Maintenance Items; Spared, Redundant, Adjustable	Type of Failure	System Protection	Failure Indications: Caution and Warning	Failure Indications: Controls and Displays	Failure Indications: IFTS Indication	Isolation Elements: Stimuli Reqmt's	Isolation Elements: System Test Points	Isolation Elements: System Test Point Voltage	Accessibility	Lost Function and Effect on Other Systems	Remarks
1. Circuit Breaker Main Bus #ME 454-0012	a. Short b. Open	a. No overload protection b. None	None	None	EPS circuit breaker panel	None	Circuit breaker leads	115 NAC 3ø, 400 cps	Semi-exposed	a. Loss of overload protection. b. Loss of control programmer (C. P.)	Out of couch function; hand bracing or velcrose bracing possible (see Figures11 and 12)
2. Waste Management Blower #ME 901-0030	a. Electrical failure b. Mechanical failure c. Leakage d. Low air flow	a. Circuit breaker b. Circuit breaker c. None d. None	a. Circuit breaker, main bus b. None c. None d. None	a. Circuit breaker popped b. None c. None d. None	EPS circuit breaker panel b. None c. None d. None	None	Blower leads	115/200-volt 3ø, 400 cps	Limited (very)	a. Loss of 5.0 CFM air flow for feces, urine and vacuum circuits. b. Loss of odor removing capability for c/m cabin	RH lower equipment bay; out of couch function; access requires: face panel removal, mounting supports for valves removal, located behind much of plumbing, RH lower equipment bay shelf. The V16-332025 removal is required (see Figure 13)
3. Cabin Temperature Control Valve 8500 28-1	Electric motor actuator failure (i.e.: burnout) (short to Gno)	Circuit breaker (CB 71)	Circuit breaker øc	Circuit breaker popped	Cabin temperature control auto-manual (to manual) S12	None	Actuator leads	115 Vac	Exposed	Loss of auto. cabin temp control. S12 (auto-manual) to manual and reset circuit breaker then no effect on other systems. If circuit breaker is not reset see next column	When circuit breaker pops cabin blower No.2 will run on 2ø, will not start if not already running (see Figure 14)
4. Apollo Guidance Computer	Short, open burned out	Circuit breakers	Failure light	See Remarks	Check failure or computer fail lights	Programmed check	None	None	Fair - AGC held in place by 12 bolts. Reached by 5' high opening. AGC Cover plates (2) held in place by approx. 24 bolts	Loss of S/C guidance control	Displays will indicate a manfunction within the function; function consists of up to 6 cards or modules

Table 3. Isolation and Task Time Analysis

IFTS/Display Monitor Indication	Stimuli Requirements	Possible Failed Units	System Protection	System T/P Connector and Pins	System Test Point Voltage	Effect on System or Systems	Isolation Task Time S/S V/S P/S	Remove, Replace, Adjust, Task S/S V/S P/S	Verification Task Time S/S V/S P/S	Total Related Task Times S/S V/S P/S
I. None	b. Visual indication (light on, circuit breaker extended, etc.)	a) Inventors b) C. P.	None	Lugs on backside	115 Vac 3 ø 400 cps	Loss of control of C.P. function, loss of ECS glycol pump, and waste "MGT" blower	5 min	12 min	1 min	18 min
II. None	(1) Audio indication (2) Circuit breaker extended	(1) Urine dump valve (2) Main circuit breaker	Explosion proof per test method 109A of MIL-STD-202	Electrical connector per MIL-C-26482 w/dual set of terminals	115/200 volt 3 ø, 400 cps	Same as lost function column, above	1 min to turn off switch on panel V16-611121 in R/H lower bay	12 to 15 hours (on ground)	15 min (on ground). Requires recording oscillograph	
III. None	Cabin temp and indicator will rise or fall depending on spare radiator orientation in relation to sun	1) Cabin temp control amp 2) Cabin temp sensor 3) Cabin temp anticipator 4) Cabin temp select (panel 13)	Circuit breaker (CB 71) Circuit breaker (CB 71) Circuit breaker (CB 71) Circuit breaker (CB 71)	Connector J1 on cabin temp control value ME 901-0217	115 v 1ø 400 N	Loss of cabin air temperature control	1 min	30 min	1 min	32 min
IV. Computer Fail and Check Fail Lights	Planned input program	Function switch modules (cards)	Circuit breakers	None	N/A	Loss of S/C guidance control	10 min	40 min (entire AGC) 43 min (remove, replace individual cards or modules)	10 min	50 min

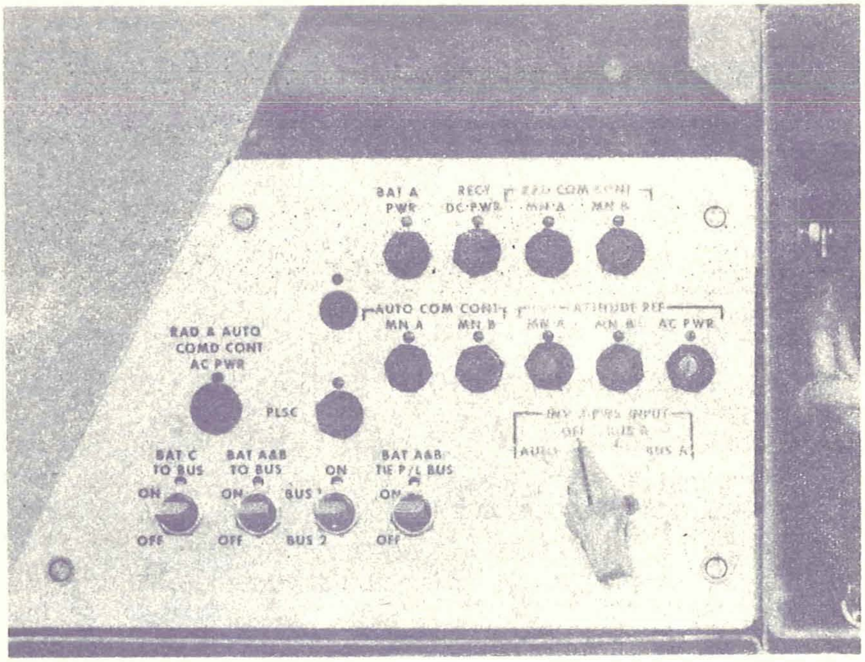


Figure 11. Power Programmer Control Panel, In Place

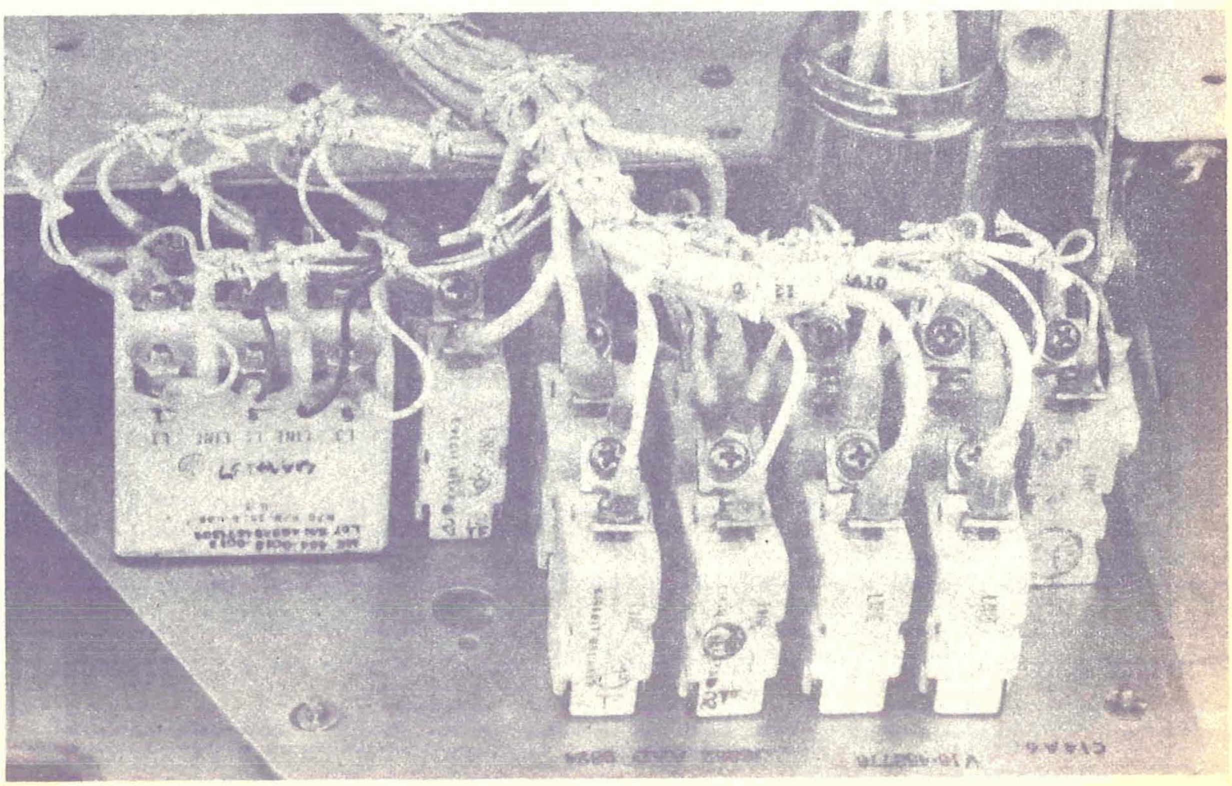


Figure 12. Power Programmer Control Panel, Removed for Maintenance

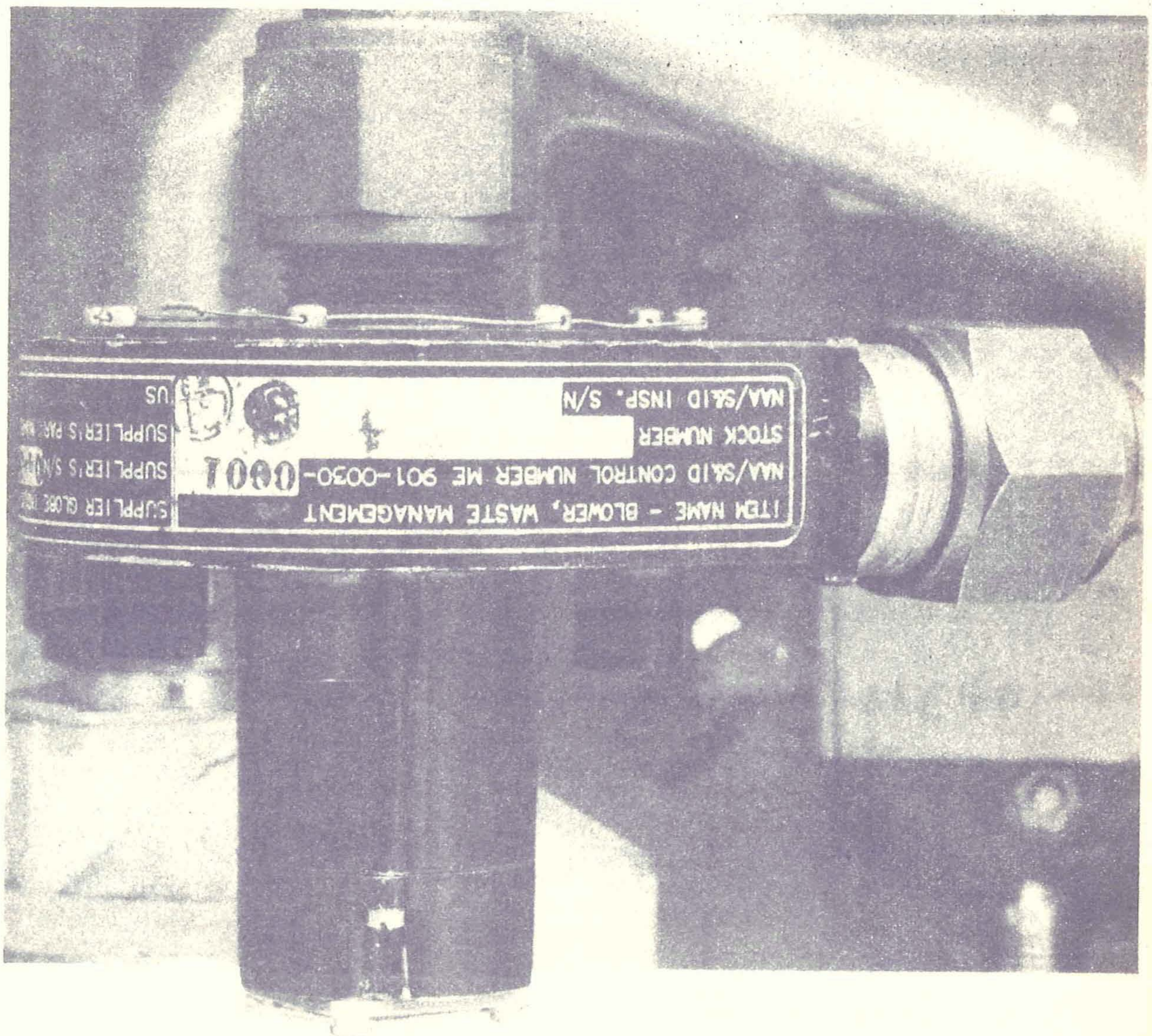


Figure 13. Waste Management Blower, In Place With Access Panels Removed

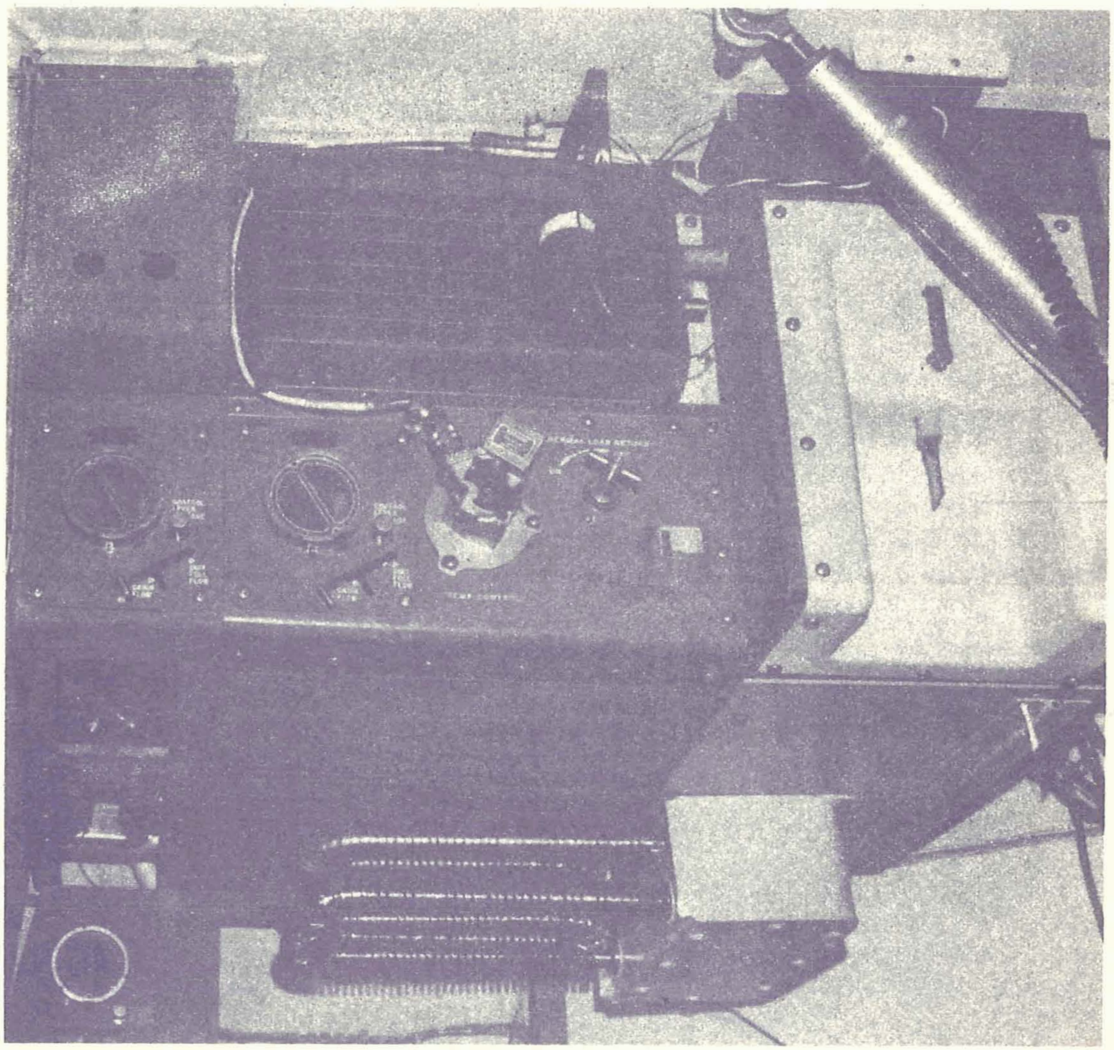


Figure 14. Cabin Air Control Panel, Showing Temperature Control Assembly (Center)

5.0 STATEMENT OF WORK

5.1 OBJECTIVES AND SCOPE

The study is proposed to determine the in-flight maintenance provisions necessary to assure at least the required functional availability and thereby extend the useful life of the Apollo spacecraft to missions of up to one year in length. The point in the potential mission duration spectrum will be determined where a maintenance concept provides a more effective and safer means of assuring mission success and/or crew survival than a pure reliability approach. The study will be based on the Apollo Block II configuration and will identify the specific failure hazards as well as the most effective means of compensating for them under the various study phase constraints.

The study is to be conducted, as shown in the logic of Figure 15, in three phases to coincide with the expected need and constraints. The Phase I effort will be limited to consideration of maintenance and provision of spares without alterations to the Block II Apollo design, Phase II will consider the introduction of minor changes to assure accessability to critical items, and Phase III will consider the complete repackaging needs imposed by up to one-year missions and acceptable crew survival goals.

This proposal covers Phase I effort only, although much of the data developed will be required for and directly applicable to the remaining phases.

5.2 STUDY GUIDELINES

All phases of the analysis will be conducted so as to logically separate the resulting changes and supporting requirements into 30-day increments as a function of mission duration and objectives. A maximum baseline mission duration of 3, 6, and 12 months for Phases I, II, and III respectively, are proposed as design goals. The analysis will be limited to the basic vehicle and life support systems to the exclusion of any purely scientific systems.

Fundamental to the analysis is the study of crew capabilities to perform the prescribed maintenance tasks in the constrained environment. To this end, S&ID proposes a limited ergonomic analysis, using available data during the two earlier phases, to assess and assure astronaut capabilities to accomplish the proposed tasks. A more comprehensive study, with some tests, is proposed for the Phase III effort.

The Apollo and AES mission success and crew safety requirements will be considered applicable goals for this analysis. However, mission success will be predicated on a definition for success which does not consider use of expendables or backup modes (either manual or automatic) as a causative for abort, except where an additional failure would endanger the crew or preclude abort. Failure therefore is defined as that situation where abort must be initiated immediately due to a malfunction for which there is no backup mode, no spare, or is nonrepairable within the time constraint.

A requirement for astronaut extravehicular activity (EVA) will not be considered a limiting factor during any of the three phases proposed, provided the tasks are expected to be within the astronauts' capability.

For purposes of the analysis, the missions will be assumed to be time extensions of the presently programmed AES missions, i.e., earth and/or lunar orbit. Further, a maximum 90-minute emergency abort profile will be assumed for the earth-orbital flights, and three days or 72 hours for the lunar orbit missions.

5.3 SUMMARY OF THE PROPOSED PROGRAM PHASE TASKS

Phase I - Analysis of Apollo Block II CSM (Phase I) - No design changes.

Analyze the existing Apollo as represented by the Phase I, Block II configuration in the manner set forth in the appendix, but within the constraints imposed by the existing design. The results will define what can be accomplished to improve the mission reliability for extended missions of up to three months in duration in 30-day increments. Emphasis will be placed on in-flight maintenance (internal and external), establishing what may be required and what can be accomplished within the ergometric limits of the crew and without change to the spacecraft configuration. The tools, spare parts, performance monitoring, and diagnostic equipment requirements will be determined, as well as the resulting improvement in mission success and crew safety to be achieved by implementing each recommendation.

Phase II - Continuance of Analysis (CSM Phase I, Block II) - Limited design changes considered.

Extend the requirements analysis of Phase I to missions of up to six months by the procedure outlined in the appendix, expressing the

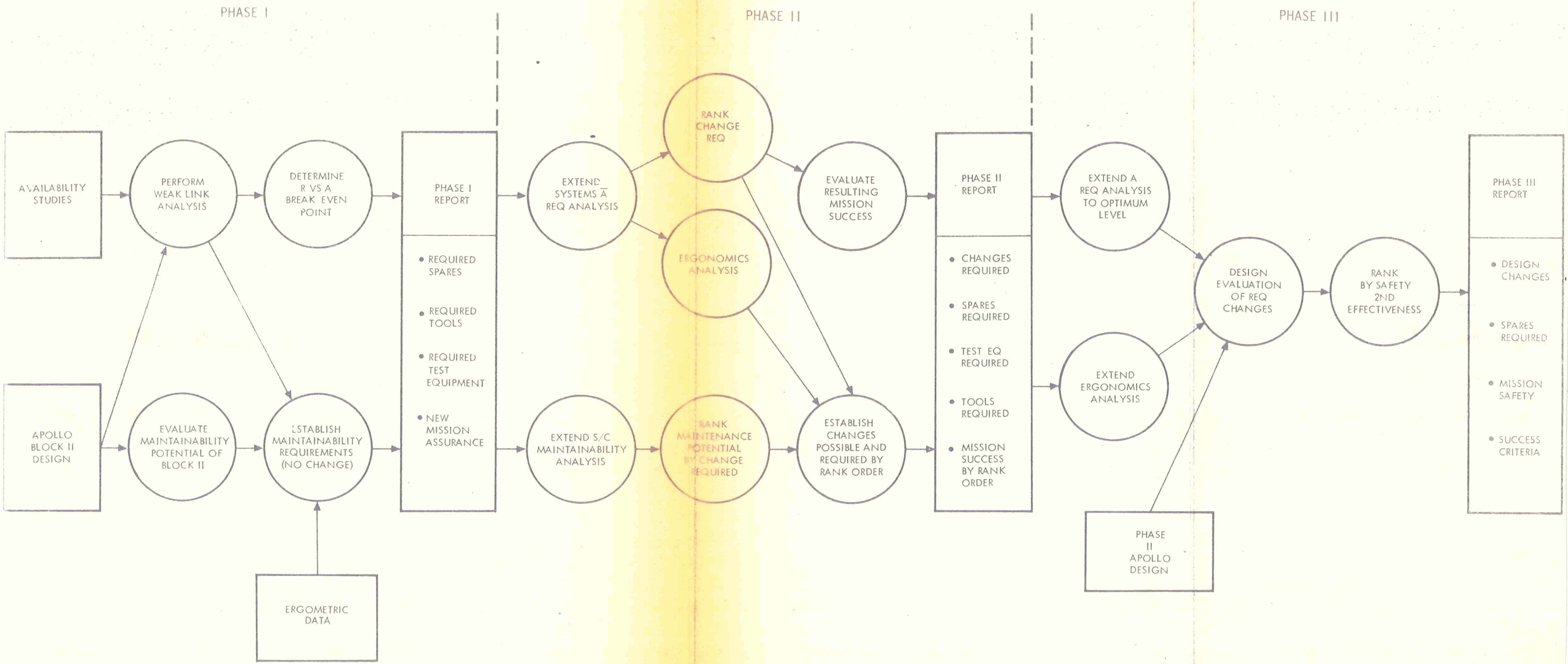


Figure 15. Availability Extensions, Study Logic

resulting requirements in terms of 30-day increments. From the requirements analysis, determine the most effective compensating action (design, operation, and/or maintenance) which can be accomplished within the constraints imposed by maintaining the present structural integrity and component-packaging represented by the Apollo Phase I, Block II CSM. The proposed modifications and spares will be limited to those essential to assure crew safety and mission success. Specific examples of possible changes are fasteners, connections, seals, access panels, plumbing, and minor changes in part or component placement. No changes in the structural members, their placement, or component design will be considered.

Phase III - Optimized Design Analysis (CSM Phase II).

Extend the requirements analysis of Phases I and II to include missions of up to one-year duration, using the method outlined in the appendix and expressing the resulting requirements in terms of 30-day increments. The analysis will establish the modifications and spares necessary to produce the most effective results in terms of mission success (vehicle systems) and crew safety. Liberal use of in-flight maintenance will be planned within the constraints imposed by known ergonomic limits and support capabilities.

Repackaging and relocation of critical functions and subassemblies will be recommended as required for accessibility within the constraints imposed by maintaining the subsystem integrity and minimizing retest requirements. Minimum redesign will be recommended for those areas not amenable to maintenance, or where effectiveness can be improved by an alternate approach; major structural changes will be avoided.

5.4 DETAILED TASK DESCRIPTIONS, PHASE I

The Phase I effort will be conducted as depicted in Figure 16, where the circles represent tasks to be accomplished under the study, while the blocks represent data already available at S&ID. The specific task descriptions are as follows:

1. Weak Link Analysis - Using the latest Apollo II reliability estimates, a list of probable failures will be derived and listed in order of relative expectancy to the extent necessary to assure achievement of the model mission objectives with at least a 0.95 probability.

2. Maintainability Analysis - Using the Apollo Block II configuration data in the form of photos, drawings, mockups, and available spacecraft, a maintainability analysis will be conducted to

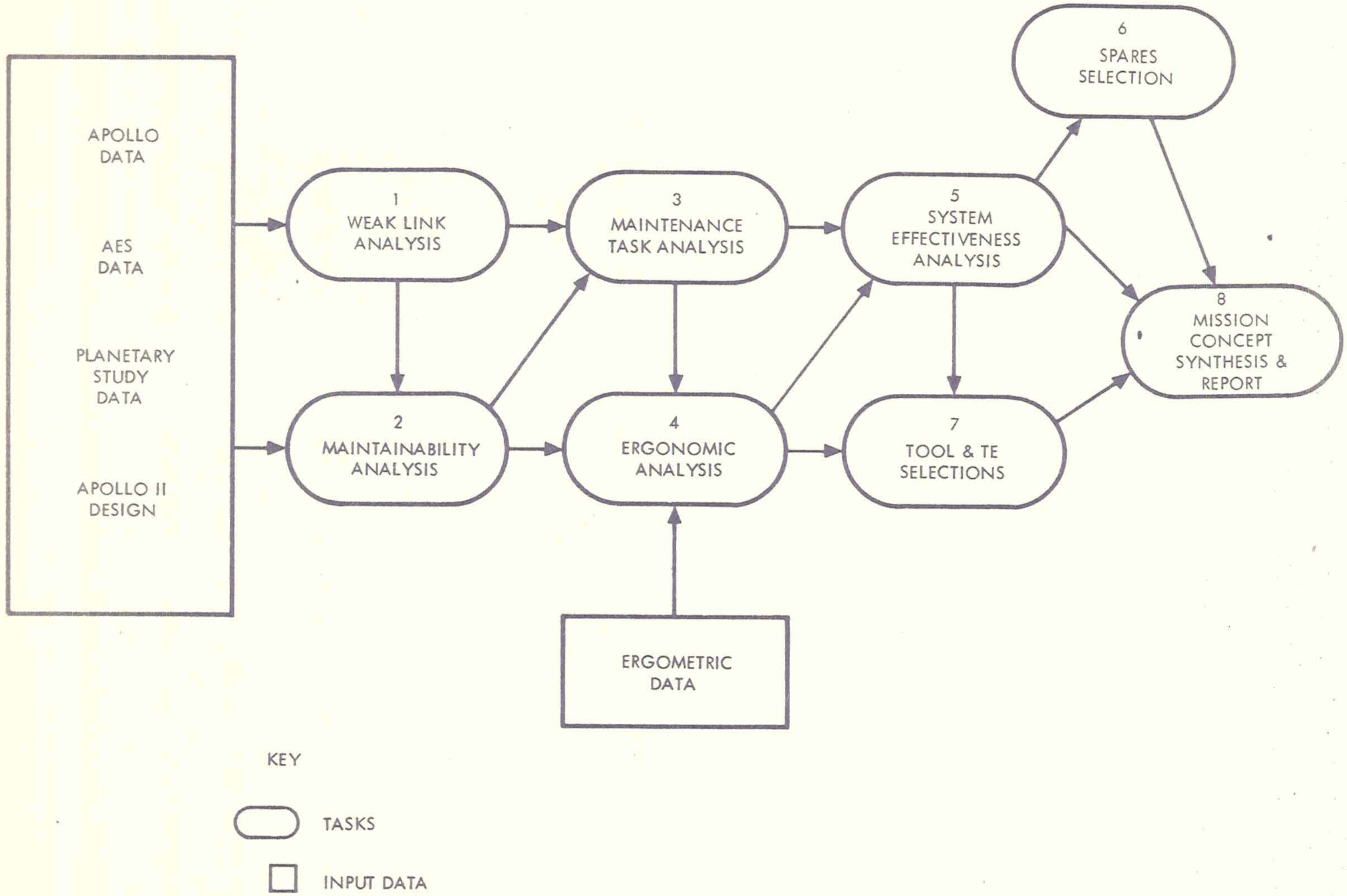


Figure 16. Detailed Task Logic, Availability Extensions Study, Phase I Effort

determine which items can be repaired and the associated problems. Photos will be taken and all available techniques will be explored.

3. Maintenance Task Analysis - Each problem isolated in Task 1 will be evaluated as to the maintenance requirement. A step-by-step task analysis will be performed and prepared in matrix form expressing the actions necessary to offset the problem through application of a maintenance routine.

4. Ergonomic Analysis - An analysis of the task requirements established in Task 3 will be accomplished to determine the requirements imposed on the astronaut. These will be compared with his expected ability to cope with them under the conditions expected to prevail as a result of the projected problem. Data established at S&ID through in-house studies will provide a major contribution to this task.

5. System Effectiveness Analysis - The data from the foregoing tasks will be analyzed to determine the most effective means of maximizing the mission success/crew safety estimate within the established constraints on spacecraft changes and astronaut capability. For each potential action capable of offsetting the problem, an assessment of the resulting reliability increase will be made and presented in matrix form (where more than one option is possible).

6. Spares Selection - From Task 5, a list of required spares, associated weight, and volume will be derived and listed in order of their relative contribution to mission success/crew survival. Justification will be provided on the basis of the contribution to the mission objectives and life expectancy.

7. Tools and Test Equipment Selection - From Task 5, a list of tools and supporting test equipment will be derived. These will be limited to only those justified on the basis of need to support maintenance of an identified failure potential.

8. Concept Synthesis, Reports, and Briefings - As a result of the total Phase I effort, a mission concept will be synthesized, expressing the effects and influences on mission objectives and life brought about by the proposed system/mission concept.

A final report and briefing will be prepared reflecting these results by the end of the fourth month, an additional 15 days each will be provided for NASA/MSC review and contractor submittal of the corrected report.

9. Project Engineering/Management - Provide technical and administrative direction for the study. This will include liaison with the customer, review and approval of reports and briefing material as well as integration and progress monitoring of the study tasks. A single point of contact for all aspects of the study will be provided.

5.5 PROGRAM SCHEDULE

The principal activities in terms of tasks and associated milestones are described in Figure 17. The Phase I effort is projected for a four-month duration with a draft of the final report to be submitted for review on 25 June 1966. This assumes that a go-ahead of 1 March 1966 is approved. One additional month has been allowed for preparation of the final report and presentation of a final briefing at the customer's facility.

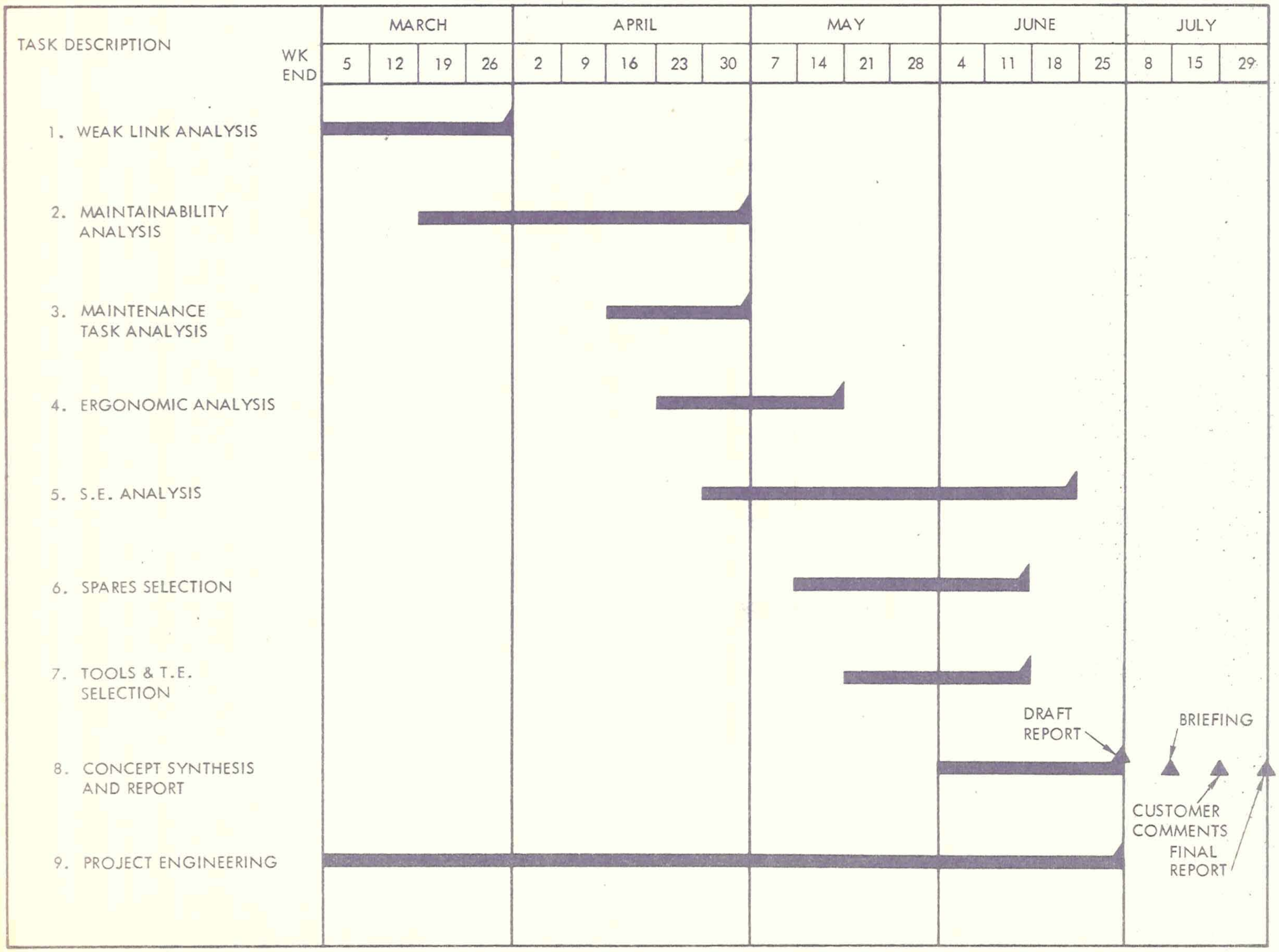


Figure 17. Availability Extensions Study, Program Milestones, Phase I Effort

ORGANIZATION

NORTH AMERICAN AVIATION, INC.

The corporate structure of North American Aviation (NAA), Inc., consists of seven operating divisions under the direction of the General Office. NAA provides outstanding management ability in the research, development, design, production, and testing of complete systems for military and civilian applications. Policy guidance in functional areas is provided by corporate vice presidents who are responsible for the application of, and divisional conformance with, these policies. Each of the operating divisions is responsible for specific areas of technological development.

Advanced research, design, and development of programs similar to the proposed study are the responsibility of the Space and Information Systems Division.

SPACE AND INFORMATION SYSTEMS DIVISION

The proposed project will be conducted by the Research and Engineering Division of NAA's Space and Information Systems Division (S&ID) located at Downey, California. Under the direction of H. A. Storms, President, S&ID continues to make significant contributions to the nation's space and lunar programs. The division is concerned with the research and development, manufacture, and launch of supersonic and transonic vehicles, including manned and unmanned spacecraft and launch and reentry vehicles.

The management and operating philosophy of S&ID is reflected in the functional staff organization chart (Figure 18), which shows the relationship among the technical, operational, and major program divisions and the proposed project organization. S&ID is project-oriented, designed to place emphasis on, and provide capability for, conducting a large number of research, development, and production activities. As indicated, the performance responsibility for this program is vested in the Systems Engineering Management Department of the Research and Engineering Division.

PROJECT ORGANIZATION

The project organization (Figure 19) has been structured to define functional responsibility. The selection and assignment of R. B. Carpenter as study project engineer was based on a demonstrated record of successful technical/management performance on research and development studies related to operations analysis. Mr. Carpenter will be responsible for accomplishing the technical objectives of the statement of work within stated cost and schedule limitations. This responsibility is exercised through the explicit authority of the project engineer to direct, redirect, approve, or reject all generated data and budgetary and schedule alignments. He is the contact with company executive management and with the customer. Mr. Carpenter will report to Mr. M. R. Kinsler, Manager of Operations Analysis who will be apprised of technical and management program status. He will arrange for interdepartment support and approve the project engineer's technical approach to the study. He will delegate necessary authority to the project engineer and assure intra-department support.

Reporting to the project engineer are E. L. Peterson, R. F. Wadsworth, and Dr. I. Streimer, who will direct maintainability analysis, reliability analysis, and ergonomics studies, respectively. In addition to his project engineer responsibilities, Mr. Carpenter will be responsible for the conduct of the systems effectiveness aspects of the program.

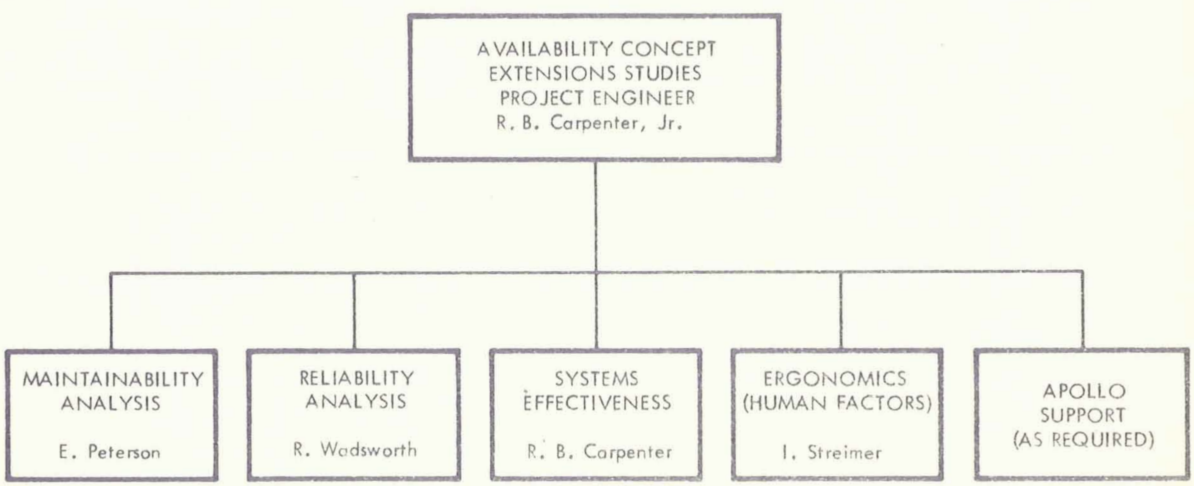


Figure 19. Project Organization Chart

Maintainability Analysis (E. L. Peterson)

Evaluate the maintainability of the Block II spacecraft relevant to the specific actions developed as potential weak links to AES. Develop the maintenance task analysis for each recommended action. Assist in tool and test equipment selection as required.

Reliability Analysis (R. F. Wadsworth)

Provide the reliability/weak link assessment capabilities. Supply the reliability assessments of the AES configuration and the expected results of each proposed maintenance action and spare recommended.

System Effectiveness Analysis and Project Engineer (R. B. Carpenter)

Perform the availability (dependability) requirements analysis of the Apollo Block II subsystems. Establish component criticality, optimum method of compensation, recommended maintenance actions, operational constraints, allowable downtime, expected missions life, monitoring, and diagnostic requirements. Assure feasibility of maintenance action proposed; recommend the most effective alternatives for mission success assurance.

Ergonomics - Human Factors - (Dr. I. Streimer)

Provide, on a consultant basis, psychological and physiological constraints, effects, and influences based on present technology to establish preliminary maintainability design criteria. Assist in evaluating task requirements. Provide consultation on man's capabilities, constraints on the maintainability concepts, and restraint requirements.

Apollo Support (Personnel as Required)

Provide data and consultant service on Apollo Block II and AES in the areas of design, reliability, maintenance capability, operational requirements, and system/component life.

Program Management (M. R. Kinsler, 100-Percent Indirect)

Provide program direction, milestone review, technical consultation and review, and budget monitoring at no cost to the contract.

PERSONNEL

The successful completion of any project is dependent on the personnel assigned. Those selected to participate on the proposed project are well qualified in their respective fields and together comprise a highly efficient organization. The biographical data presented in the following paragraphs briefly describe the current responsibilities and the technical, scientific, and educational background of S&ID personnel planned for participation in the proposed project.

M. R. KINSLER, Manager, Operations Analysis, Systems Engineering

Mr. Kinsler will be responsible for the program management of the study. His experience includes more than 17 years in the aerospace industry. Since jointing Operations Analysis as Manager, he has been responsible for directing the efforts of highly technical personnel engaged in research and development of a wide variety of DOD and NASA contracts, proposals, and company research and development programs. These programs include mission and operations requirements analysis for EVA, lunar exploration, rescue missions, lunar mapping, and sophisticated defensive systems. Prior to this position, he was Manager of the Apollo Environmental Control System Group, responsible for the analysis, design, and testing of nuclear radiation protection, structure and equipment temperature control systems, and the thermal and atmospheric control system. He spent three years with the NACA at the Lewis Laboratory as a research scientist. Subsequently, he worked two years at Brooklyn Polytechnic Institute as a research associate while studying applied mechanics. Mr. Kinsler started with NAA's Los Angeles Division where he was responsible for X-15 temperature control, environmental control, and propellant pressurization systems analyses and test functions. Accomplishments included space vehicle preliminary design projects, such as Mercury, Space Stations, Space Logistics Transport, Dyna-Soar, Advanced X-15, Lunar Soft Landing Vehicle, and Aerospaceplane. He also conducted analyses of atomic weapon delivery, IR detection of ICBM's and decoys, reaction kinetics of autoignition, ablation, and others.

Mr. Kinsler holds a BSME from the City College at New York and a MME from Case University. He has developed a number of new techniques in aerodynamics and thermodynamics. In addition, he has for the past six years demonstrated a capability to manage and direct the efforts of others.

R.B. CARPENTER, JR., Senior Technical Specialist, Operations Analysis, Systems Engineering Management

Mr. Carpenter will be responsible for requirements analysis. His experience includes more than 22 years in electronics in the aerospace industry. Since joining the Operations Analysis group at S&ID, he has been responsible for systems effectiveness analysis work, conducting studies in extended space operations requirements analysis and the establishment of associated effectiveness design criteria. He developed and successfully applied a specialized form of effectiveness analysis which resulted in demonstrating the feasibility of extended manned space missions by optimized maintenance and controlled operational procedures. The concept provides for maximizing the benefits available from both man, machine, and the man-machine interface resulting in maximized effectiveness. Three papers have been requested for presentation on various facets of the approach. Some specific programs involve Apollo extended missions, manned Mars/Venus flyby, and lunar exploration missions. While in military service, he administered and directed the activities of electronics and communication system overhaul and modification, at the depot level. Subsequently, he acquired six years of experience at the Air Force Research Electronics Laboratory. The work included basic research communications and radar systems design, development, and evaluation. While with General Electric Company, he accumulated three years in design engineering and five years as senior engineer and supervisor in Product Assurance (now Reliability), conducting engineering evaluation, test, redesign, and operational suitability evaluation of radar and communication systems. At the Electronics Systems Division, USAF, Bedford, Massachusetts, he was Technical Director, Reliability and Maintainability. There he established and implemented reliability and maintainability programs for major ground electronics systems such as SAGE and BMEWS. At S&ID, he has been responsible for establishment and execution of the reliability and qualification test programs for all systems, equipment, and parts associated with Apollo. For two years, he was responsible for reliability study efforts in support of new business activities. He has developed a number of advanced studies, and has evolved and applied new concepts of reliability engineering and testing for the manned spacecraft era. Mr. Carpenter studied electrical engineering at Syracuse and Northeastern Universities. He is presently studying for his Master's degree in systems engineering at West Coast University. In addition, he has taken advanced courses in electronics, reliability engineering, and management. Mr. Carpenter has published numerous papers on reliability with emphasis on maintainability and availability concepts, including the following.

1. Effective Design for Interplanetary Exploration via the Availability Concept, presented at Twenty-Eighth National Meeting, Operations Research Society of America, Houston, Texas (4 November 1965).

2. Demonstrating Reliability for Long Space Missions, presented at Eleventh National Symposium on Reliability and Quality Control, Miami Beach, Florida (12 January 1965).

3. Reliability for Manned Interplanetary Travel, presented at Fourth Annual Reliability and Maintainability Conference, AIAA, Los Angeles, California (28 July 1965).

4. A Reliability Concept for Long Space Missions, presented at Fourth Manned Spaceflight Meeting, AIAA, St. Louis, Missouri (12 October 1965).

5. Apollo Reliability by Demonstration or Assessment, presented at Tenth National Symposium on Reliability and Quality Control, Washington, D.C. (29 January 1965).

6. Demonstrating Reliability, Theory vs Practice, IEEE Spring Seminar on Reliability Testing (April 1965).

7. How Big is the Space Flight Maintenance Problem?, National Conference on Space Maintenance and Extravehicular Activity, Orlando, Florida (1966).

8. Systems Effectiveness Key to the Planets, Third National Space Congress, Cocoa Beach, Florida (1966).

E.L. PETERSON, Maintainability Admistrator, Advanced Logistics

Mr. Peterson will be responsible for maintenance system development on the proposed study. He has held his current position for the last two years. In four years with NAA, he has derived maintainability concepts for proposal activity, developed a maintainability program plan outline for NASA, contributed to the development of an operational readiness program for Apollo, and performed research in the areas of optimizing training, technical data presentation, and maintainability. He is responsible for the definition of maintainability programs within the Apollo, Saturn S-II, and WS-131B programs. From 1941 to 1962, Mr. Peterson was in the Air Force, where he worked through all enlisted grades, three warrant officer grades, and retired as a major. Fifteen of these years were spent in electronics and aircraft maintenance, and six were spent in training activities. During the last three years with the Air Force, he was Chief of the Air Force's Hound Dog missile training program, and received the

Air Force's Commendation Medal for excellence in this effort. Mr. Peterson holds a Bachelor of Science degree in electrical engineering from the University of Oklahoma, which he earned on a full-time scholarship from the Air Force Institute of Technology. He is a member of Eta Kappa Nu (national honary electrical engineering society) of the IEEE and the professional groups on education, military electronics, and reliability. He was guest lecturer on maintainability at the U.S. Army Management Engineering Training Agency and at the University of California at Los Angeles (UCLA) Engineering Extension Division.

In the field of maintainability, Mr. Peterson has recently published:

1. Maintainability Design Requirements for Future Space Systems, AIAA/AFLC/AFSC Support for Manned Flight Conference, Dayton, Ohio (April 1965).

2. Operational Readiness - A Decision Making Took for Reliability-Maintainability Management, AIAA/ASME/SAE, and others, Fourth Annual R & M Conference, Los Angeles, California (July 1965).

3. Maintainability Design Requirements Derived from Operational Readiness Goals, ASQC Product Maintainability Seminar, Philadelphia, Pa. (October 1965).

R.F. WADSWORTH, Project Engineer, Reliability Advanced Programs

Mr. Wadsworth has been with S&ID for 5 years. He currently supervises the Reliability Advanced Programs activity and is responsible for developing technical reliability material in support of advanced proposal and study activity and providing support for small hardware programs. He has participated in the reliability portion of a number of S&ID advanced systems study efforts, Modified Apollo Logistics Vehicle, Extended Mission Apollo, Extended Apollo Systems Utilization Study, MORL, Ten-Passenger Reusable Orbital Transport, and has provided support to the Apollo Applications Program. Before joining S&ID, he was associated with Douglas Aircraft Company from 1959 to 1961, where he coordinated training requirements for training equipment. During his 20 years in the Navy, he served in various administrative and operational positions at sea and ashore. He directed the Navy's aviation fuel and lubricants program for two years, including both the research and service aspects. He served on the NATO Standardization Committee for Petroleum Products and was a member of the NACA subcommittee on fuels and lubricants. Before his retirement in 1959, he was director of training on the staff of the Chief of Naval Air Technical Training. Mr. Wadsworth holds a Bachelor of Science degree in electrical engineering from the United States Naval Academy and received his Master of Science degree in aeronautical engineering from Massachusetts Institute of Technology. He is the coauthor of several technical papers on reliability and quality control which have been presented at national symposia.

Mr. Wadsworth has written the following papers:

1. Logistics Tomorrow - Support in Space, IAS, Aerospace Support and Operations, Orlando, Florida (4-6 December 1961).

2. Apollo Reliability Control Program, IAS Reliability Control Payoff, 31st Annual Symposium, New York (21-23 January 1963).

3. Logistics Functions in Engineering Development, IAS Meeting on Large Rockets (October 1962).

I. STREIMER, Research Specialist, Life Sciences, Research and Engineering

Dr. Streimer will head the human factors section of the proposed study project. As a research specialist with S&ID since 1963, he has developed programs of research in the area of man's work output capabilities in spacesuited and reduced-traction environments, and also has provided inputs of the same nature to Advanced Systems for use in proposals. Dr. Streimer led in the development of a low-mass, six-degree-of-freedom simulator. He established a research program utilizing the simulator, in which various effects of different mass ratios and work outputs are being investigated. From 1958 to 1963, he was with Boeing Company as a physiologist-biophysicist, serving successively as Chief of Human Factors Research, Chief of the Biophysics Group, and Chief of Operator Capability Studies. He developed the Boeing four-degree-of-freedom simulator, and directed ergonomic and biomechanical studies which produced data descriptive of man's force - and work-producing capabilities and characteristics under a variety of conditions. He also developed a medical instrumentation program, currently holding three patents on miniaturized medical instrumentation, and conceived, designed, developed, and executed the preliminary phases of the target identification and reconnaissance programs. At New York University, College of Engineering, Research Division, from 1956 to 1958, he designed and executed research programs in biomechanics of prosthetic and orthotic devices. From 1952 to 1956, he was chief chemist at Pathe Laboratories, Inc. Dr. Streimer received a Ph. D. in experimental psychology and biophysics from New York University, a Master of Science degree in physiology and physiological psychology from the City College of New York, and a Bachelor of Arts degree in chemistry and physics from Brooklyn College.

Dr. Streimer is the author of numerous papers in the field of ergonomics research, including the following:

1. Effects of Variations in Operator Output Characteristics on Space Logistics, NAA S&ID, SID 64-1425 (July 1964).

2. "Human Output Characteristics During Specific Task Performance in Reduced Traction Environments," Human Factors, pp. 121-126 (April 1964).

3. "An Investigation of the Effects of Pressure Suit Wearing on Work Output Characteristics," Aerospace Medicine (August 1964).

4. Some Bio-energetic Considerations of Space Flight and Their Implications to Systems Designers, ASME WA/HUF (December 1964).

5. The Effect of Reduced Gravity and Pressure Suits Upon Operator Capability, Amer. Psych. Assoc. Eng. Div., Los Angeles, California (6 September 1964).

6. "Logistics Considerations Derived from Variations in Operator Output Considerations," Aerospace Medicine, Vol. 35, No. 12, pp. 1163-1166 (December 1964).

RELATED EXPERIENCE

Successful completion of the proposed study depends not only on the technical skills of the study team members and the managerial capability residing in the contractor organization, but also on the existence of a significant body of technical knowledge gained from previous experience, particularly from Apollo. The sufficiency of technical data available to the study team and an indication of S&ID's competence in pertinent areas are presented in this section.

As a major systems contractor, S&ID has demonstrated capability in the definition and establishment of advanced aerospace systems and information systems. This capability has placed S&ID in the forefront of industry as prime contractor and systems manager of the nation's most ambitious manned space program, Project Apollo. The Apollo program imposes the most vigorous reliability requirements ever encountered upon design and development and, conjointly, the requirement to establish effective maintainability concepts, procedures, techniques, and equipment.

The developmental planning of manned interplanetary missions that has occurred as a natural outcome of the Apollo program has focused increased attention on the need for a concept of maintainability for vehicles in space. Failures will occur during extended space travel, and maintenance is becoming essential to mission success and crew safety. Therefore, it is necessary to know the characteristics and specific modes of failure as well as the constraints of downtime limits, weight allocation for spares, maintenance time requirements, tools, and diagnostic and performance monitoring requirements.

S&ID has performed extensive research and development work in these and all other pertinent aspects of the maintenance problem through numerous contracts as well as company-sponsored study programs. The resulting technical data have been documented and verified and are available for use in the proposed study.

CONTRACTS

Performance Under Weightlessness (AF 33(616)-6911)

This program conducted for the Air Force Flight Accessories Laboratory, Wright Air Development Division, consisted of an analytical and experimental study of human performance under conditions likely to be encountered in space. The work included an investigation of the use of hand tools by man to perform maintenance, assembly, and repair tasks under weightless or near-weightless conditions. Within the framework of anticipated manned space missions, tasks requiring tools were identified and tools available for the performance of these tasks were evaluated for adequacy in terms of predicted limitations in human performance. Suggested modifications of conventional tools and development of new tools were made subjects of the study. The requirements for the development of multipurpose tools were specified, as well as the development of new techniques for fabrication, assembly, and construction in space. During the course of the space tools study, several experimental studies were conducted using air-bearing platforms to simulate the absence of gravity. These studies included investigation of rotary pursuit task performance, torquing task performance, force application under friction and near-frictionless conditions, and determination of man's moment of inertia.

Analytical Maintenance Model (AF 33(615)-1330)

Under contract to the Aeronautical Systems Division, USAF, S&ID has completed a 12-month research study investigating space system maintenance problems. An analytical model was developed that can be used for making comparisons in research and development activities aimed at providing a maximum maintenance capability for space systems. The methodology and associated computer simulation program used in the development of the model were derived from company-sponsored research studies.

The analytical model interrelates the maintenance parameters of a space system throughout its useful mission life. The model produces and illustrates the effects of the interaction of maintenance parameters in the form of output data, presented so that analysis of the data will facilitate the development of a maintenance and support system simultaneously with the development of the hardware system. During the course of the study, areas that required trade-offs among design, maintainability, reliability, performance, and actual costs were determined.

Although the model simulated a manned orbiting space station of long-duration mission, the program logic was general in its description of the parametric interactions, and is applicable to any system configuration. Of particular significance to the proposed study, the model includes operational parameters for in-mission maintenance as well as prelaunch, ground-based operations.

Manned Mars and/or Venus Flyby Vehicle Systems Study (NAS9-3499)

The primary objective of this study was to determine the feasibility of performing early flyby missions to Venus and Mars using hardware being developed for other NASA spaceflight programs. A secondary objective was to establish the extent to which the flyby mission can accomplish scientific objectives. The preparation of preliminary conceptual designs, development schedules, and costs were additional objectives. The applicability of current developments to provide the functions required on the flyby mission was established. The Apollo level of technology is adequate to assure development of a reliable and safe spacecraft. A detailed analysis was made of the environmental control (ECS) and life support systems (LSS) for crew safety based on maintainability for the long-duration mission. A preliminary, less-detailed analysis was made of the total spacecraft. The logic employed in designing for maintenance involved analysis of subsystem loops, one assembly at a time. It was determined that successful system operation can be achieved through crew repair and maintenance actions.

The original scope of this effort was extended to include additional study to implement maintenance and availability analysis (as part of the reliability analysis). The results indicated that a design concept based on the availability concept with on-board repair of subsystems can provide a workable spacecraft for long-duration manned missions such as the Mars and Venus flyby within the limits of present technology.

Study of Subsystems Required for a Mars Mission Module (NAS9-1748)

The study was conducted to develop information on a manned Mars mission module subsystem that can be used by NASA to support and identify design criteria for future space systems. The two-part investigation involved a study of subsystem requirements for a Mars mission module and an analysis of manned Mars spacecraft configuration and aerodynamic braking. During part one, a design study was completed of the module and analyses were made of the required subsystems, failure effects, reliability, maintainability, development, and cost. A maintenance concept was developed, taking into consideration all governing factors involved in the mission, operational requirements, and the major constraint of time. Both scheduled and unscheduled (preventive and corrective) maintenance functions were investigated. Other considerations involved definition of a maintenance priority system, checkout procedures, cannibalization, support data, tools and equipment (both standard and nonstandard), spare parts, and training for maintenance activities.

Project Apollo (NAS9-150)

S&ID is prime contractor for Project Apollo, the leading data source for establishing the requirements for manned space systems. Throughout the Apollo program, reliability and maintainability have been critical factors, involving thousands of hours of study, investigation, research, and development. Problem areas have been investigated thoroughly and design criteria have been established. These studies have yielded data that have permitted the formulation and implementation of comprehensive training courses for astronauts, the development of advanced training machines, and the establishment of the details of every operation and equipment with which they might conceivably be associated in both normal and emergency modes.

The data resulting from these studies and the knowledge and experience of this group are available to the program team and should contribute substantially to the achievement of program objectives.

Stabilization System Test Model (AF 33(615)-2616) (For Astronaut Back Pack, et al)

A contract recently was negotiated with the Air Force Aeronautical Systems Division for the development and testing of a feasibility demonstration model of an extravehicular astronaut attitude control system based on the principle of angular momentum exchange utilizing control-moment gyros. The test model is being designed either for astronaut use as a back pack or for use in unmanned, remotely controlled operations in midspace, and will include six control-moment gyros, associated reaction jets, gas supply, and torque motors for the application of attitude commands. The feasibility of the concept has been proved by experimental and analytical studies at S&ID. Further theoretical support has been provided by a computer simulation program. The 11-month contract will culminate in the delivery and field-testing of a demonstration model.

COMPANY-SPONSORED STUDIES

Engineering Study and Preliminary Design of a One-Man Propulsion Device for Lunar and Free-Space Environments (PA 6492)

The primary purpose of this study was to provide NASA with the necessary methodology, performance data, and preliminary design details to permit the identification of a one-man propulsion device for use in free-space and on the lunar surface. Mission requirements and goals were defined and methods and equipment for crew training established. A major consideration was the compatibility of the device with the spacecraft, spacesuit, and anticipated environments.

Earth Orbital Apollo Applications (R&DA 6112)

This study determined the operational and configurational characteristics of Apollo spacecraft modified for three distinct mission applications: (1) earth-orbiting laboratory, both zero g and partial g; (2) logistics crew transfer and resupply; and (3) maintenance and rescue operations. Modifications to current Apollo spacecraft and systems to accomplish mission objectives were defined with special emphasis on definition of new system concepts where existing systems were inadequate. Subsystem design criteria and operational procedure were defined for the three vehicle configurations where current Apollo information was inadequate. Included in the study was consideration of the effects of long-duration orbital storage, extended habitability, long-duration subsystems concepts, and increased personnel and payload capabilities on operational requirements.

Self-Maneuvering Unit for Orbital Maintenance Worker

S&ID conducted an extensive independent study project to define orbital maintenance work requirements and human capabilities to perform under weightlessness. Because of the excessive restrictions placed on motor tasks by existing pressure suits, the study sought to project data to describe a true spacesuit that would provide acceptable freedom of movement and comfort over an extended time. One specific objective of the study was to determine the characteristics of an optimum propulsion-stabilization unit that would be used in conjunction with the suit or an encapsulation. A complete orbital maintenance analysis was outlined.

Criteria for Optimizing Maintenance and Supply Resources for Manned Space Systems (R&DA 6097)

The purpose of this study was to determine maintenance and life support logistics requirements for any system operating in cislunar space. The study included the investigation of requirements for both routine and emergency ferrying, maintenance, and supply missions.

Maintenance Aspects of Extended Space Operations (SID 65-1484)

The company-funded study presents a broad view of in-flight maintenance in extended space operations. It defines the maintenance functions and support requirements insofar as current equipment design will allow. The importance of an activity in which human performance makes a significant contribution to the life extension of a system is indicated. The study provides the guidelines that, after being modified to meet specific mission and systems constraints and requirements, must be considered as essential in the development of an effective in-flight maintenance plan for the support of any space program.

Kinesthetically Controlled Devices for Maneuvering in Space and Low-g Environments (R&DA 6176)

S&ID has been exploring the feasibility of applying kinesthetic control to small, one-man propulsion devices. The feasibility of this type of control has been demonstrated and tested in two test beds of one-man maneuvering units - one concept suitable for lunar traverse which was demonstrated at one gravity (see Figure 20), and the other concept suitable for extravehicular operation which was tested in a zero-g KC-135 aircraft at Wright-Patterson AFB.

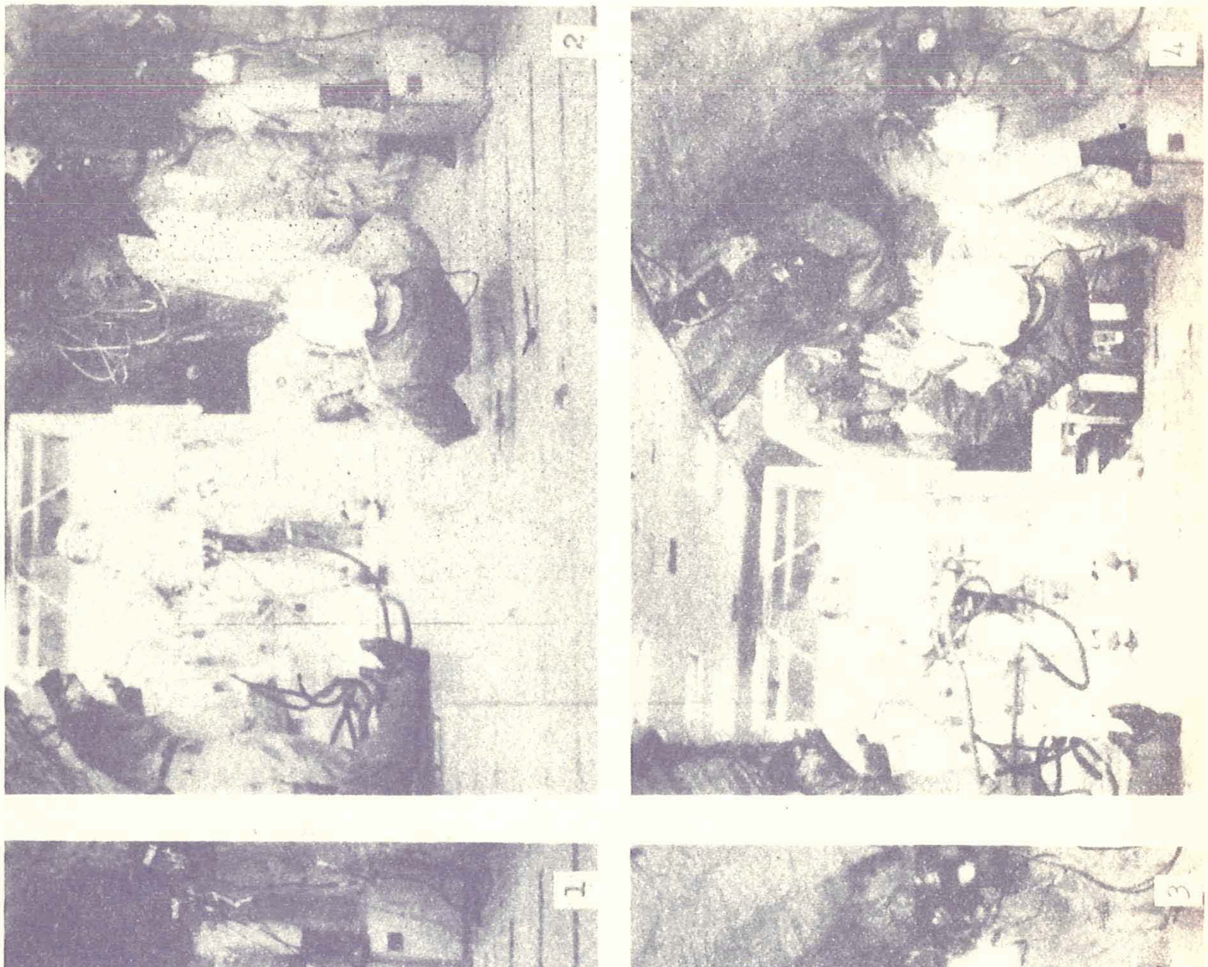


Figure 20. Zero-G Translation Sequence

FACILITIES AND EQUIPMENT

The major portions of work on the proposed program will be performed at the S&ID complex in Downey, California. This facility consists of both Government-owned and company-owned buildings, which have functional and support areas capable of providing engineering, manufacturing, administrative, and test services required in meeting anticipated project objectives. A description of the particular facilities to be used in performance of the efforts is presented below.

S&ID FACILITIES

Project Administration and Engineering

The Space and Information Systems Division is located 16 miles southeast of Los Angeles, in Downey, California. The engineering and administrative offices to be used by the project team are located in an S&ID-leased building (Building 305), which is the headquarters of the management and engineering personnel of S&ID's Research and Engineering Division. No additional facilities or equipment will be required to conduct the effort described in this proposal.

Computing and Simulation Center

Digital computer support (IBM 7094) for the proposed project will be provided by S&ID's Engineering Computer Center. The ECC is located in NAA-owned facilities in Downey, California. Major items of computer equipment include two IBM 7094's, one 7040, two 7010's, four 1460's, one 1620, nineteen 100-amplifier analog computers for computation and engineering analysis, and a Stromberg-Carlson 4020 CRT plotter. In addition, ten 1410's are used primarily on projects similar to the proposed project for business data reduction.

Technical Information Center and Library Facilities

S&ID's Technical Information Center, in addition to containing more than 100,000 documents and periodicals on aerospace topics, has incorporated a UNITERM, or prime-word fast retrieval system, to help research engineers obtain specific and related technical data in their fields of interest. Nearing completion and already in use is an automation program that includes an automated circulation control system, computer-produced indexes utilizing coding and permutation techniques to provide access to the total collection by author, subject, source, counter number, document number, and ancillary data. Computer-based search and information retrieval, selection dissemination of information, and automated acquisition and periodical accountability functions are being installed. The total effort is closely allied to the Defense Documentation Center services and to the NASA information systems.

Because of favorable plant location, S&ID personnel also have quick access to the Pacific Aeronautical Library, University of California at Los Angeles, University of Southern California, Los Angeles Public Library, and California Institute of Technology.

APPENDIX

APPENDIX I. SAMPLE PROCEDURE FOR THE CONDUCT OF AN AVAILABILITY ANALYSIS

THE SCOPE AND OBJECTIVE

This appendix details the step-by-step procedure to be followed in the conduct of an availability analysis of known system design and its associated configurations. The approach is therefore based on the premise that the design is essentially complete and that the associated reliabilities are known or can be computed. It is applicable to those designs where the reliability is expected to be marginal or low, and where man is available and capable (not incapacited) for some form of maintenance and/or control action.

The intent of the analysis is to determine the specific needs in terms of failure of the system and the most effective method of meeting it, and through a planned response, elevate its potential reliability and/or crew safety to a satisfactory level. To accomplish this end, failure must be redefined. For the purposes of this analysis, failure is defined as an unpredicted loss of a given function for which no spare is available, or where the expected time to repair will exceed the downtime constraint and result in a compromise of the associated objective.

The apparent risk of failure (reliability or crew safety goal) must first to set at a safe but reasonable level. For maximum effectiveness, there can be two or more levels depending on the criticality of the system function. For purposes of this analysis, and within the vehicle systems restriction, only two classes of criticality are apparent: those associated with crew survival and those more pertinent to crew convenience. These obviously do not deserve equal weighting, even from the mission success point of view, since failure of a crew function may require abort while failure of other functions may result in loss of some data or a convenience.

The objective of this analytical approach is to isolate and specifically identify all weak links in a given system function, and, by implementing the most effective/safe means feasible, equalize the apparent risk of failure and reduce it to the preselected level.

THE APPROACH

The approach to the maintenance requirements determination is dependent on the system reliability model and the relative accuracy of the reliability estimates. For that reason, the data should be taken from the same source where possible; this reduces or eliminates the effects of differences between failure rate tables and the respective collection and reduction errors.

The approach to the problem is illustrated in the logic diagram of Figure A-1 which is constructed on the assumption that the reliability logic and hazard estimates are completed as is the case for the Apollo Block II. Given these data as a baseline, they can proceed along the lines delineated in the referenced logic and detailed in the following steps:

Step 1. Assess the Reliability or Failure Hazard.

Using the best reliability and failure-mode data (history and test results), the reliability or failure hazard associated with each pertinent system, subsystem, component, assembly, and part is determined. A system or mission success model is synthesized in logic form reflecting the individual contributions to success and/or crew safety. A failure hazard or reliability is associated with each block in the logic for each identifiable level of assembly.

> Note: The absolute accuracy of the data is not so important as the relative accuracy. Since the intent is to isolate weak links, the relative values are most significant. In areas where realistic data are not available, a failure mode analysis (FMA) provides a good estimator, particularly when any of the failure modes can be related to known data. This technique is illustrated in Figure A-2, where a method of changing subjective failure mode data into failure hazard data is illustrated.

Step 2. Determine Optimum Level for Availability Application

Probably the most important problem to be solved during the analysis is the establishment of the optimum level of assembly for availability corrective action, whether this action be preparation for maintenance, operation control, redesign, redundancy, or any combination. Any of these actions may be accomplished at the system, the subsystem assembly, or part level. Determination of the optimum level of assembly for availability application is made on the basis of the criteria listed under step 3 and illustrated in the following.

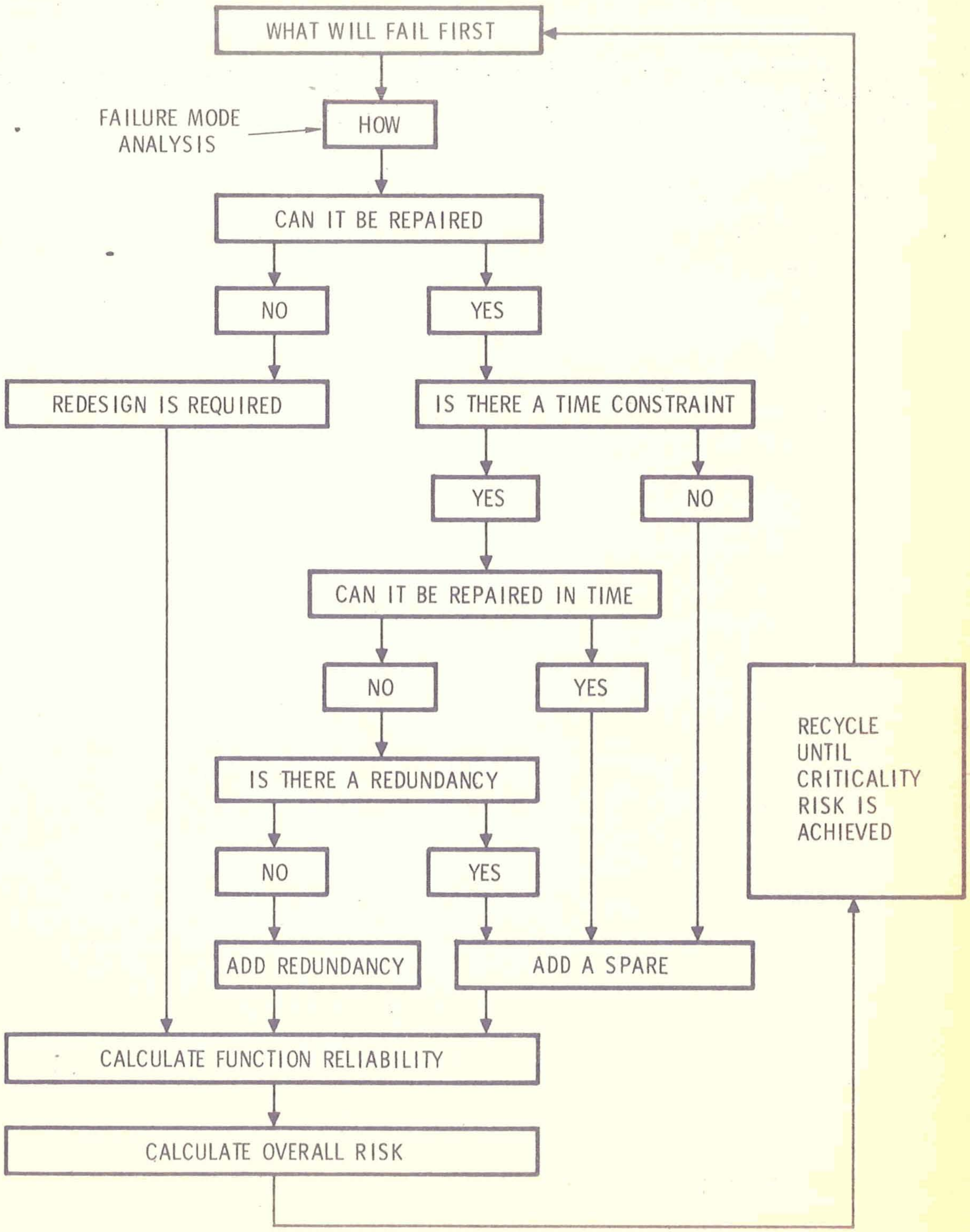


Figure A-1. Logic of Requirements Analysis

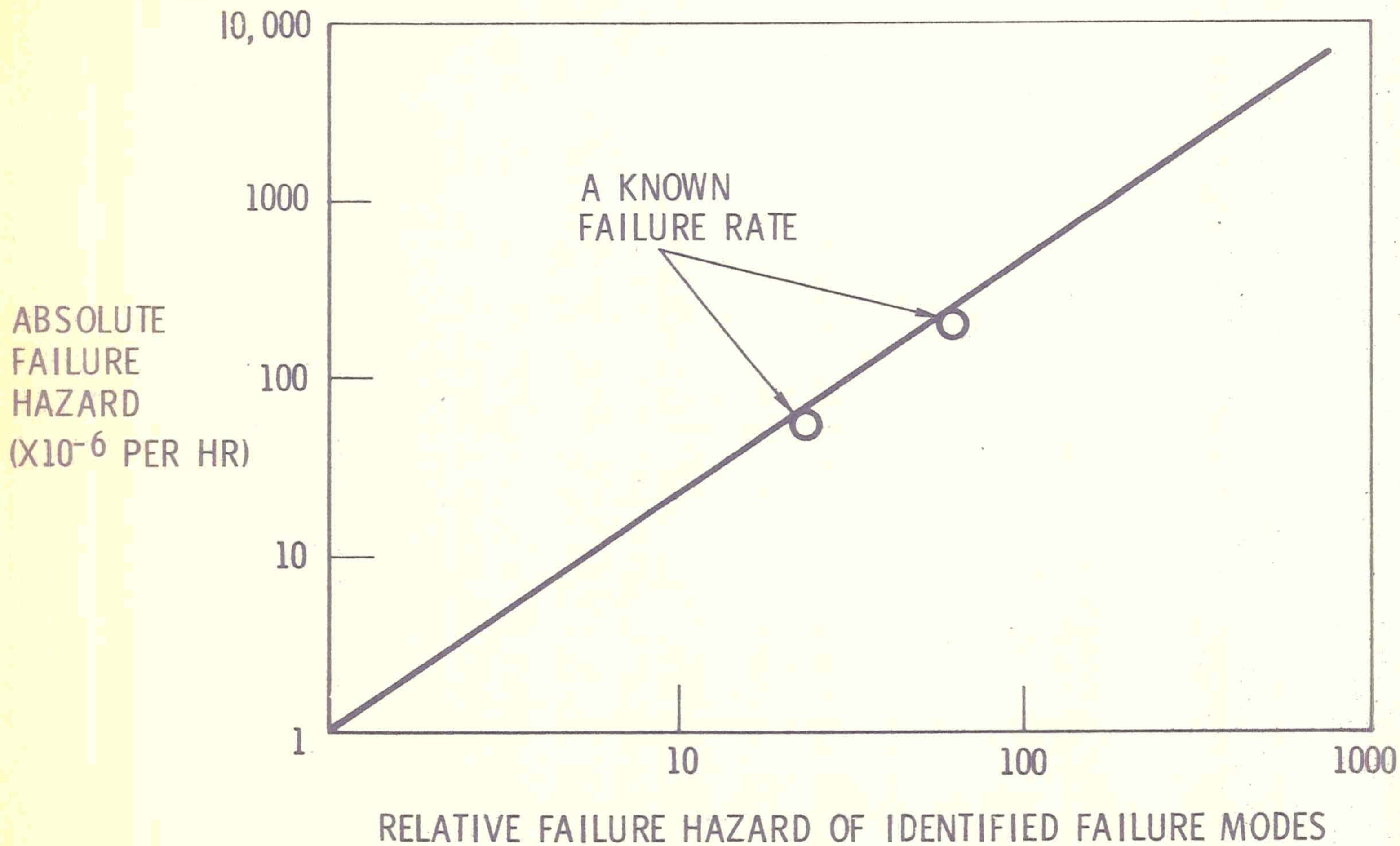


Figure A-2. Finding the Absolute Failure Hazard (Rate) From a Failure Mode Analysis

Figure A-3 relates the problem of level selection and the process. To determine the most appropriate level to improve design deficiency, it is necessary to determine how failure risk is distributed within and among the specific system, functions, assemblies, or parts. From the example, note that at the system level only one function displays a low reliability or relatively high risk. At the assembly level, only one assembly still contributes most of the failure hazard. However, at the part level, three provide an equal risk of failure. One spare or redundant assembly which contains all those parts will eliminate the need for spares for the three parts and the associated work time, performance monitoring, and diagnostic equipment and time. If the spare assembly is small and lightweight, easy to diagnose, and easy to replace, the choice is an obvious one.

Note: Because of the strong interface between Step 2 and Step 3, several iterations between these steps are usually required before a discrete and optimum solution is selected.

Step 3. Determine the Most Effective Design Action.

The key to this phase of the analysis is determining the most effective/safe corrective action required to reduce the failure hazard and provide a means of offsetting the expected failure event. Each weak link must be treated as an individual case. First, the most probable failure mode or modes are isolated and the appropriate action subsequently determined. Arguments for the selection of the most effective action are:

- Accessibility (can it be reached by the astronaut?)
- Least number of spares (minimizes spacecraft weight and volume)
- Least number and complexity of repairs (minimizes crew activity and chance for error).
- Ease of maintenance (minimizes downtime and chance of error).
- Least redundancy (minimizes complexity and weight, redundancy is less desirable because interchangeability of spares is reduced)
- Simple monitoring and diagnosis (reduces complexity and maintenance time)

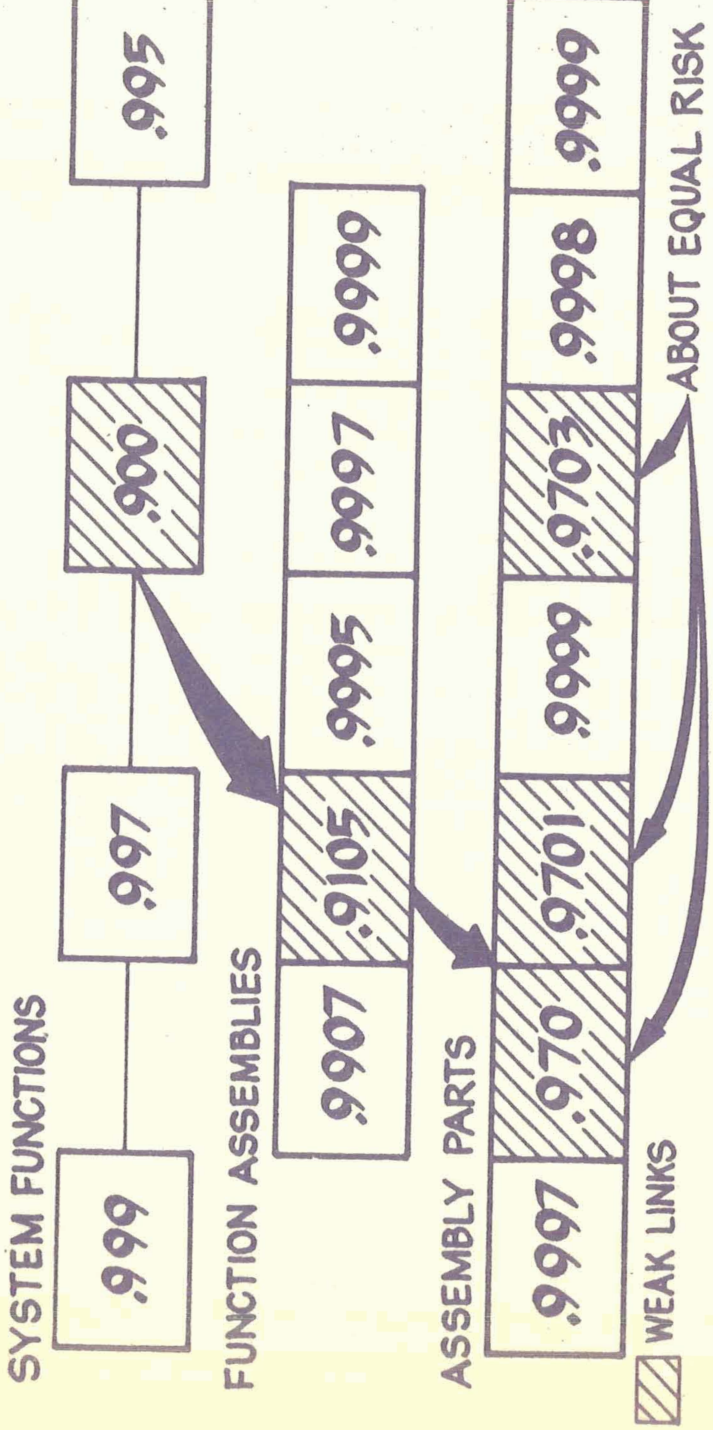


Figure A-3. Optimizing Effectiveness by Equalizing Risk

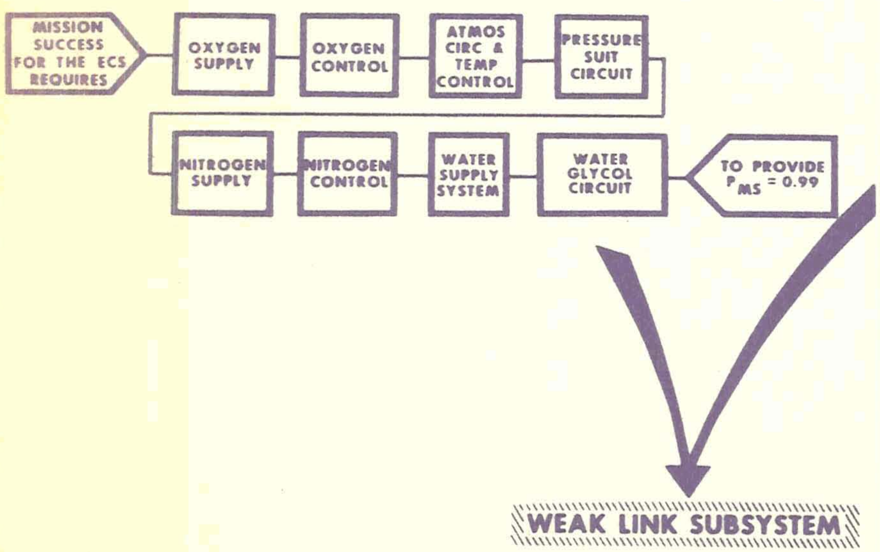
Selection of the most effective action may best be illustrated by reference to a selected example. From the associated table in Figure A-4, it is obvious that the water-glycol (W-G) loop is the weakest link and should be treated first. Referring to the next level of assembly illustrated in Figure A-5, the W-G loop is further subdivided into identifiable assemblies containing parts not easily separable, thereby precluding the usefulness of a further breakdown. The most effective level of assembly to maximize design availability may be found by manual trial or sometimes by computer simulation.

No specific ground rules can be set for determining the most effective action, since each problem must be considered on the basis of the most likely failure mode and individual design constraints. In the ECS example, three different cases are treated. One weak link was identified as the space radiator, and the primary failure mode was expected to be a meteoric puncture. Since repair or replacement may be impractical, a simple system redesign was the better alternative. The total required area could be divided into a larger number of sections, reducing the effect of a single puncture in one; overdesign would provide additional total area and reliability. As another example, the outlet check valves were not easily accessible, and a redundant valve was a more effective approach since it introduced the least complexity and redesign activity. As a final example, the cabin temperature control was easily accessible and therefore best if spared (refer to Figure 14). These are typical of the type of decision process required for each potential failure mode. The process continues. The new risk is determined after each fix, and the next weak link is resolved until the acceptable risk level has been reached or surpassed.

The need for individual attention to each potential failure mode cannot be over-emphasized. The use of computer techniques for this part of the analysis is very limited. Each decision is usually different and discrete. A computerized model is useful for isolating the weak link areas (but not the failure mode) and for determining the status of the overall failure risk after each fix and/or the resulting effect of each of the candidate fixes.

EXAMPLE - MISSION MODULE ECOLOGICAL CONTROL SYSTEM

ECS FUNCTIONAL DIAGRAM



ECS MISSION RELIABILITY

SUBSYSTEM	APPORTIONED MARS FLYBY REQMT	PREDICTED RELIABILITY MARS FLYBY (700 DAY)
PRESS. SUIT CIRCUIT	0.99933	0.96484
ATMOS CIRCUIT & TC	0.99985	0.99197
WATER/GLYCOL	**0.99271**	**0.65800**
O_2 SUPPLY & CONTROL	0.99910	0.95300
N_2 SUPPLY & CONTROL	0.99962	0.97960
WATER MGMT	0.99939	0.96740
ECS RELIABILITY	0.9900	0.56875

Figure A-4. Failure Analysis – Attacking Problem

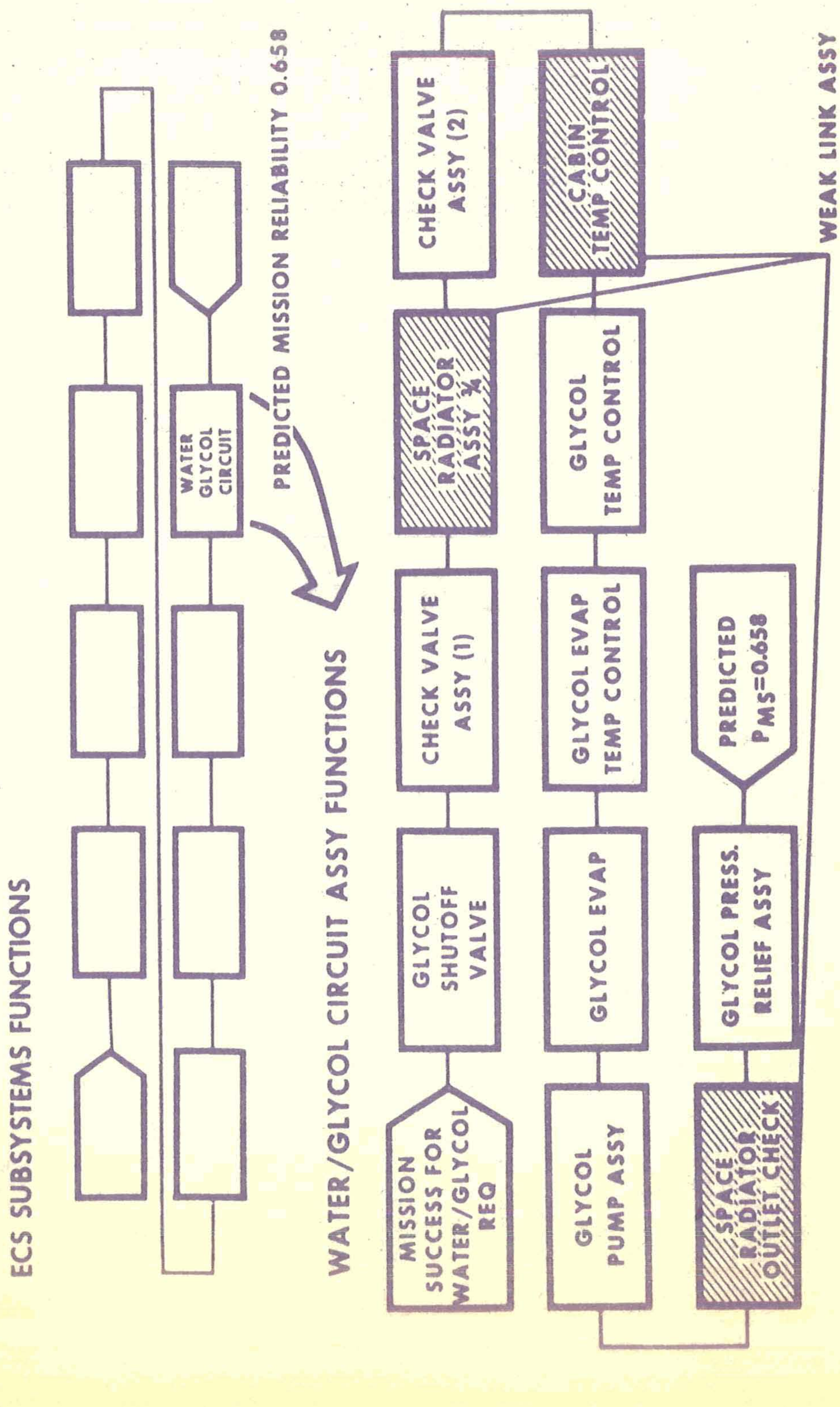


Figure A-5. Subsystem to Assembly Level Logic